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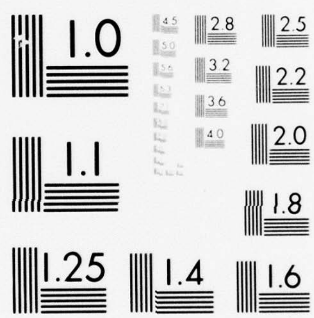

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STRUCTURAL DESIGN OF PAVEMENTS FOR LIGHT AIRCRAFT

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FINAL REPORT

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Prepared for

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FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
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16. Abstract

This report presents structural design criteria for airfield pavements to be used by light aircraft; i.e., those with gross weights less than 30,000 lb. Presented are criteria for conventional flexible and rigid pavements, for rigid and flexible pavements containing stabilized layers and membrane-encapsulated soil layers, and for unsurfaced areas; a cost-benefit analysis; and a construction guide for thin concrete pavements.

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PREFACE

The investigation reported herein was sponsored by the Federal Aviation Administration (FAA) under Inter-Agency Agreement No. DOT-FA75WAI-526, "Structural Pavement Design for Light Aircraft." The FAA technical representative was Mr. Fred Horn (ARD-430).

The investigation was conducted during the period January 1975-December 1976 at the U. S. Army Engineer Waterways Experiment Station (WES) by personnel of the Soils and Pavements Laboratory (S&PL) under the general supervision of Messrs. James P. Sale and Richard G. Ahlvin, Chief and Assistant Chief, respectively, of S&PL. This report was prepared by Mr. Donald M. Ladd, Dr. Frazier Parker, Jr., and MAJ A. Taboza Pereira.

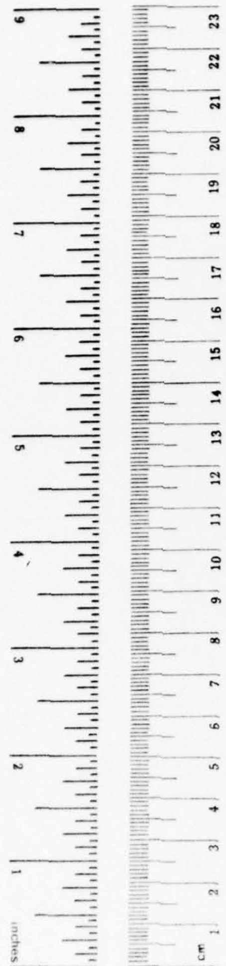
Directors of WES during the conduct of this investigation and the preparation of this report were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

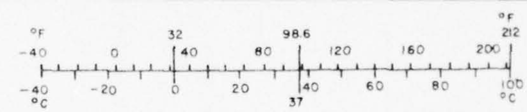
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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STRUCTURAL DESIGN OF PAVEMENTS FOR LIGHT AIRCRAFT

INTRODUCTION

PURPOSE

The purpose of this study was to develop pavement design procedures for light aircraft. (Pavements for light aircraft are defined as those intended to accommodate aircraft with gross weights less than 30,000 lb.*)

SCOPE

Criteria were developed based upon state-of-the-art technology; i.e., no extensive field or laboratory testing program to generate information was conducted. The basis for the criteria was primarily a downward extrapolation of information developed for pavements designed for heavier loadings, supplemented and/or modified with performance data available from existing pavements that have been designed for and subjected to loadings comparable to that of light aircraft. The areas investigated and discussed in this report are:

- a. Conventional flexible pavement design.
- b. Conventional rigid pavement design.
- c. Design of rigid and flexible pavements containing stabilized layers.
- d. Design of pavements containing membrane-encapsulated soil layers (MESL).
- e. Unsurfaced soil area design.
- f. Cost-benefit analysis.
- g. Construction of thin rigid pavements.

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* A table for converting units of measurement is presented on page 2.

CONVENTIONAL FLEXIBLE PAVEMENT DESIGN

THICKNESS REQUIREMENTS

Thickness design curves were developed for conventional flexible pavements to be used by light aircraft. These curves were developed using criteria developed by the Corps of Engineers (CE).[1] The criteria are based on results of numerous tests conducted by the CE including studies of test sections trafficked with full-scale loads. The flexible pavement design procedure is also based on an analysis of these test results. The criteria used herein were also used to develop current Federal Aviation Administration (FAA) design curves which are presented in FAA Advisory Circular AC 150/5320-6B.[2]

DESIGN PARAMETERS

The design criteria presented herein involve the use of several significant parameters, including load, load distribution, load repetitions, strength, and thickness. The first three are concerned with the loading delivered to the pavement, whereas strength and thickness are concerned with the pavement and the materials of which it is constructed. Load distribution is further broken down into tire pressure or contact pressure, contact area, number of tires, and tire spacing. Strength is considered in terms of the California Bearing Ratio (CBR) for evaluating shear resistance and the ability to resist densification.

LOAD

Load is normally the most significant parameter in pavement design. The design curves presented herein treat load in terms of gross aircraft weight. This weight was considered to be distributed so that 95 percent of the gross weight was on the main landing gears.

LOAD DISTRIBUTION

The load on a wheel is applied to the pavement by a tire; thus, tire pressure is an important parameter in pavement design. (Contact pressure is the real concern of designers but is not a readily established quantity.) Rather than a direct treatment of tire or contact pressure,

tire contact area is treated as the parameter, in which case it is considered that load, pressure, and contact area are interrelated by the equation $P = pA$ in which P is wheel load, p is tire inflation or contact pressure, and A is tire contact area.

One means of improving distribution of load is the use of multiple wheels on a single landing gear assembly. In this way, the load is divided between two or more wheels rather than one. To consider the effects of multiple-wheel loads, use is made of the equivalent single-wheel load (ESWL) concept. ESWL may be defined as the load on a single wheel that will have the same effect on a pavement structure as the load of an entire multiple-wheel assembly.

LOAD REPETITIONS

In working with the design criteria, load repetitions were dealt with in terms of annual departures. As treated herein, the criteria are for a 20-year life. Therefore, a curve for 600 annual departures represents 12,000 total departures over the life of the pavement.

STRENGTH

Strength considerations include the ability of the pavement to resist shear deformation and densification. The strength of soil in regard to its resistance to shear deformation is assessed by use of the CBR. Densification is controlled by establishing requirements to be attained by compaction during construction so that densification will not be significantly further increased by aircraft loads on the pavement during its design life.

THICKNESS

Thickness of overlying construction is the parameter which determines the protection of a layer of given strength from the load applied to the pavement surface above it. A material of any given strength can be protected against shear failure and densification from any given loading by a layer of proper thickness. Therefore, designing to protect the subgrade, subbase, or base from shear deformation or densification consists of selecting an adequate thickness with which to cover it.

DEVELOPMENT OF DESIGN CURVES

Procedures have been developed for preparing design curves and are reported in References 1 and 3. These procedures make use of the following formula for calculating required thicknesses:

$$t = \alpha\sqrt{A}\left[-0.0481 - 1.1562\left(\log\frac{CBR}{p}\right) - 0.6414\left(\log\frac{CBR}{p}\right)^2 - 0.4730\left(\log\frac{CBR}{p}\right)^3\right] \qquad (1)$$

where

t = total thickness required above supporting layer, in.

CBR = measure of soil strength

α = load repetition factor which varies with number of wheels on main gear of aircraft considered and the volume of aircraft traffic, coverages (Figure 1). The number of coverages is determined by dividing the number of aircraft departures by a departure-to-coverage ratio. The ratio used for single-wheel gears was 7.94 and for dual-wheel gears was 5.2

A = tire contact area, sq in. The tire contact area used for single-wheel gears was 127 sq in. and for dual-wheel gears was 75 sq in.

p = single-wheel load (SWL) or ESWL tire pressure, psi. For single-wheel gears, $p = SWL/A$; for dual-wheel gears, $p = \frac{ESWL}{A}$, where ESWL is determined by the method shown in Reference 3. This is an artificial tire pressure for dual wheels consistent with use of the contact area of one tire and has no relation to actual tire pressure. However, for single-wheel loads, this pressure is the actual average contact pressure and is nominally the same as the tire inflation pressure

ESWL = equivalent single-wheel load, lb, computed for the dual-wheel gear aircraft using one gear with tires spaced at 18 in. center-to-center

These parameters are also related by the curve shown in Figure 2 since Equation 1 describes this curve.

The design curves produced from these criteria are presented in Figures 3 and 4. Figure 3 is for light aircraft having single-wheel landing gears, and Figure 4 is for light aircraft having dual-wheel landing gears.

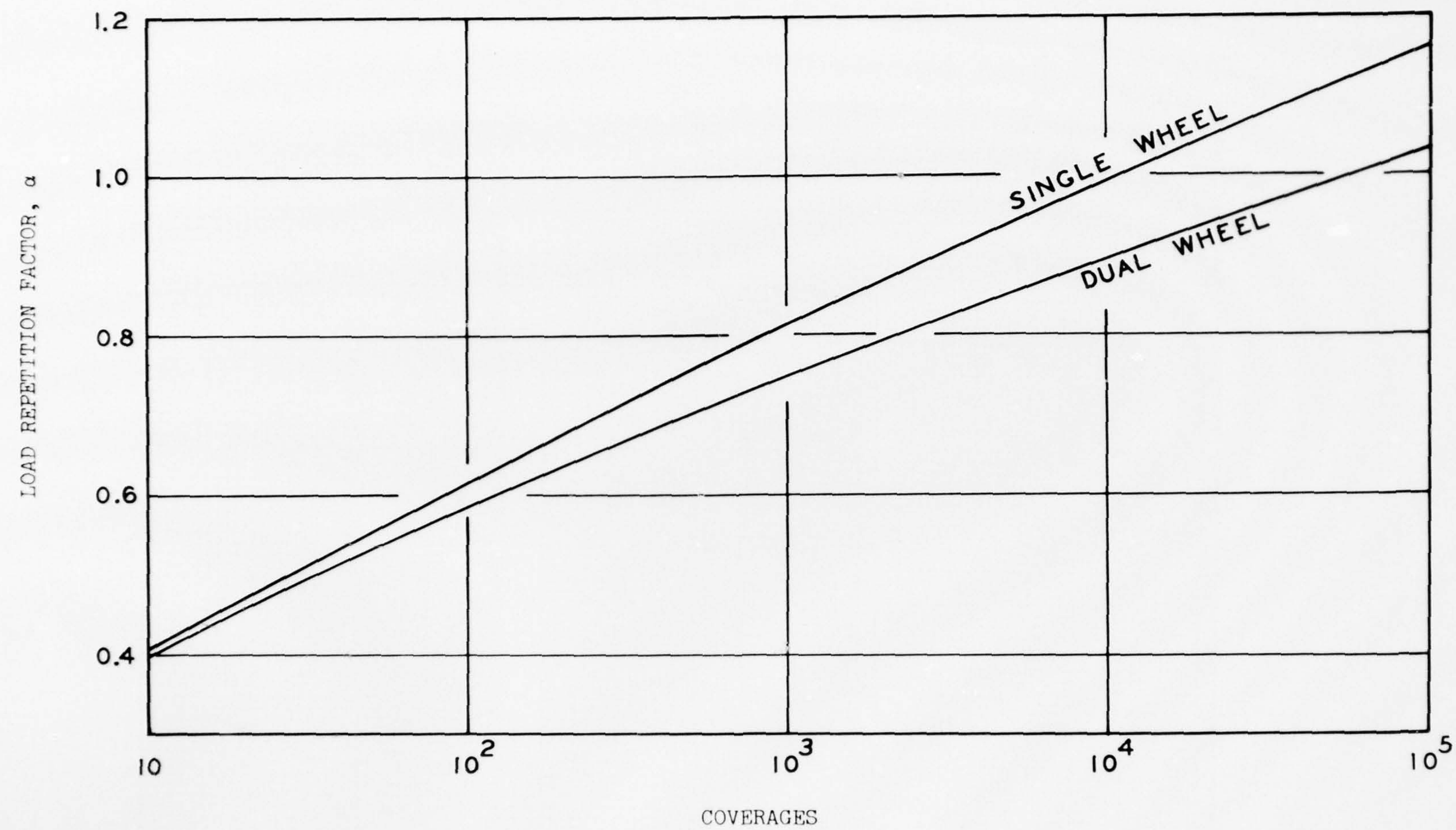


Figure 1. Coverages versus load repetition factor

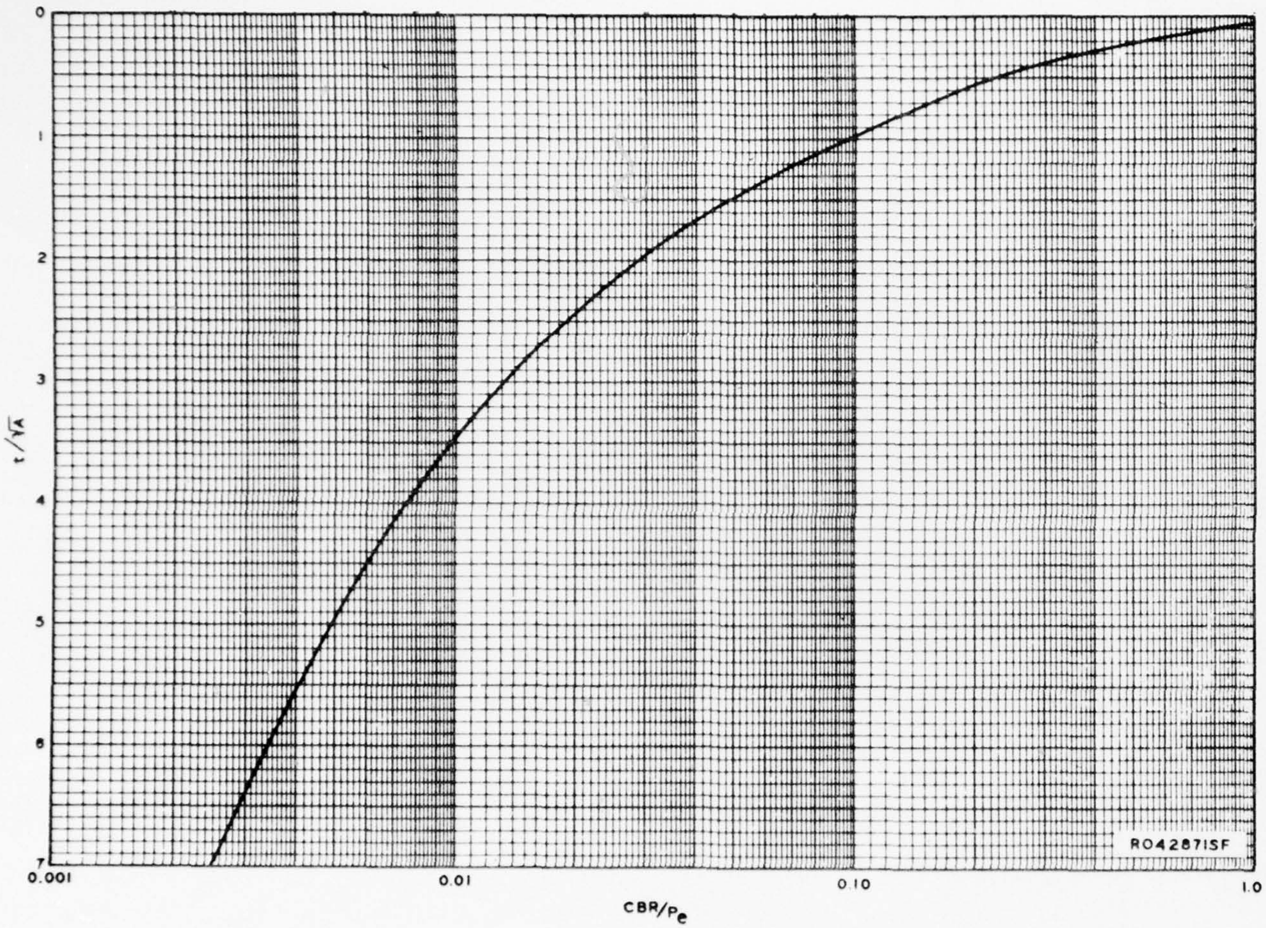


Figure 2. Complete $\frac{t}{\sqrt{A}}$ versus $\frac{CBR}{p}$

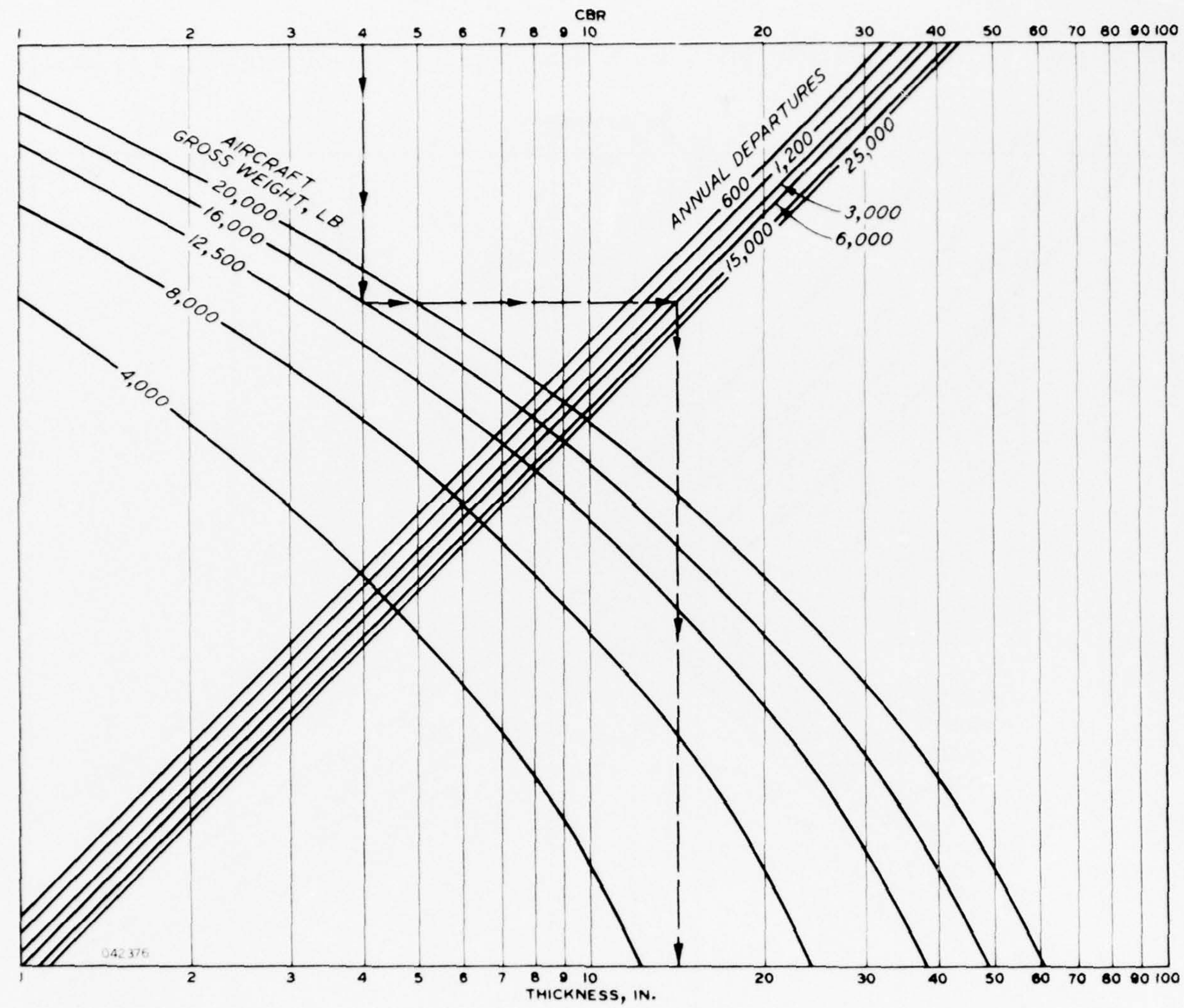


Figure 3. Flexible pavement design curves for light-load aircraft, single-wheel gear

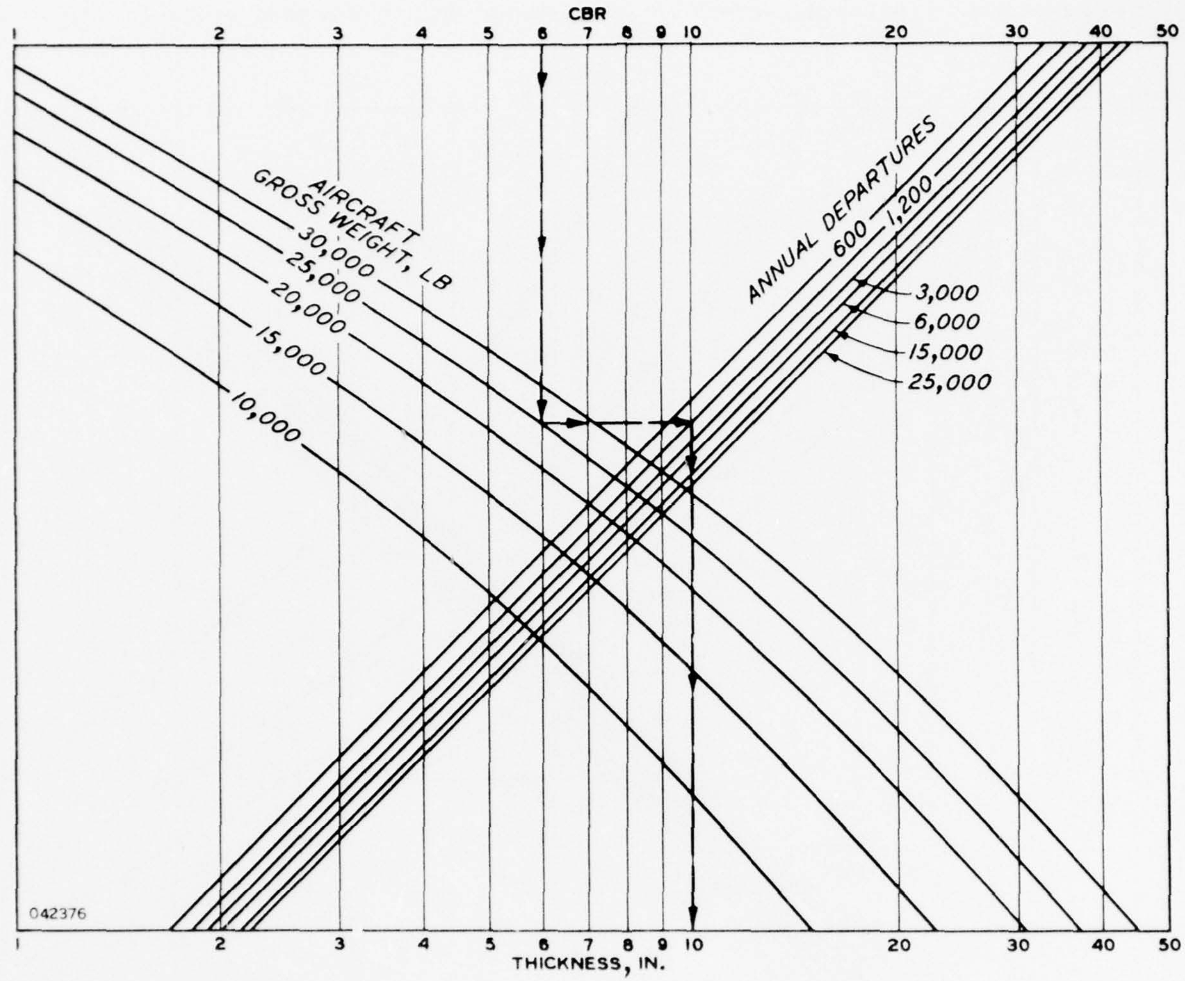


Figure 4. Flexible pavement design curves for light-load aircraft, dual-wheel gear

MINIMUM THICKNESS REQUIREMENTS

In addition to determining total thickness and layer thicknesses from the design curves, there is also a requirement for minimum thickness of pavement and base course. These minimum thicknesses are as shown on the following table, and are adequate for small business jets with high tire pressures except that surface treatments should not be used where foreign object damage may occur to aircraft.

Table 1

Minimum Thickness Requirements

Gross	100-CBR Base		80-CBR Base		50-CBR Base	
Weight, kips	Pavement	Base	Pavement	Base	Pavement	Base
			Single-Wheel Aircraft			
4.0	ST	4	MST	4	MST	6
8.0	MST	4	MST	4	1-1/2	6
12.5	1-1/2	4	2	4	2	6
16.0	2	4	2	4	2-1/2	6
20.0	2	6	2	6	3	6
			Dual-Wheel Aircraft			
10	ST	4	MST	4	MST	6
15	MST	4	MST	4	1-1/2	6
20	1-1/2	4	2	4	1-1/2	6
25	2	6	2	6	2	6
30	2	6	2	6	2-1/2	6

NOTE: ST denotes surface treatment; MST denotes multiple surface treatment.

MATERIAL REQUIREMENTS

BITUMINOUS SURFACING

The bituminous surface or wearing course must prevent the penetration of surface water into the base course; provide a smooth, well-bonded surface free from coarse particles which might endanger aircraft or persons; resist the stresses imposed by aircraft loads; and furnish a

texture with good nonskid qualities yet not so abrasive as to cause undue tire wear. To successfully fulfill these requirements, the surface must be composed of mixtures of aggregate and bituminous binder which will produce a uniform surface of suitable texture, stability, and durability. Bituminous materials specified in AC 150/5320-1A[4] may be used. In addition, materials meeting specifications used by state highway departments for construction of interstate highways may be used to construct surface courses for light aircraft pavements.

BASE COURSE

The base course is the principal structural component of the flexible pavement. It has the function of distributing the wheel load stresses to the underlying layers. The material in the base course must be of sufficient quality and thickness to prevent shear failure and densification in the subgrade and of sufficient strength to resist stress induced into the base course itself. The quality of the base course depends upon composition, physical properties, and compaction. FAA specifications[4] for various types of base courses are designed to ensure quality materials. In addition, base course specifications used by state highway departments in constructing interstate highway pavements may be used in specifying base course requirements for light aircraft pavements.

SUBBASE COURSE

Where total thickness requirements dictate, a subbase will be included as an integral part of the flexible pavement structure. The function of the subbase is similar to that of the base course. However, since it is protected by the base and surface courses, the material requirements are not as strict as those for base course. FAA Specification Item P-154, "Subbase Course,"[4] covers the subbase requirements. In addition, subbase specifications used by state highway departments in constructing interstate highway pavements may be used in specifying subbase courses for light aircraft pavements.

COMPACTION REQUIREMENTS

BASE COURSE

The base course will be compacted to 100 percent density as determined by the compaction control test specified in FAA T-611.

SUBBASE COURSE

Subbase courses will be compacted to 100 percent density as determined by the compaction control test specified in FAA T-611.

SUBGRADE

Compaction of the subgrade will be as follows:

a. For cohesive soils, the top 6 in. will be compacted to 90 percent of FAA T-611 maximum density.

b. For cohesionless soils, the top 6 in. will be compacted to 95 percent of FAA T-611 maximum density.

c. Fills will be compacted to 90 percent of FAA T-611 maximum density.

DESIGN EXAMPLE

Assume that it is desired to design a flexible airfield pavement for the following conditions:

a. Aircraft gross weight = 16,000 lb.

b. Aircraft landing gear = single-wheel.

c. Design traffic = 6000 annual departures.

d. Clay (CL) subgrade material = 4 CBR.

e. Base course material = 80 CBR.

f. Subbase course material = 50 CBR.

To determine the thickness requirements, enter Figure 3 with the 4 CBR value, move downward to the 16,000-lb gross weight curve, then horizontally to the 6000 annual departure line, and then vertically to the thickness scale. The total thickness required above the subgrade is 15 in. From Table 1 obtain the minimum pavement and base course thicknesses. These are 2 in. of bituminous concrete and 4 in. of base course. Using these minimum thicknesses, the thickness of subbase will be 15 in. - 6 in. = 9 in. Therefore, the total section will be as follows:

2-in. bituminous concrete surface

4-in. 80-CBR base course

9-in. 50-CBR subbase

4-CBR subgrade

Compaction of the base course, subbase course, and subgrade will be as follows (from the section above entitled "Compaction Requirements").

Materials used for base courses will be compacted to at least 100 percent of FAA T-611 maximum density. Where it can be shown that a higher density can be obtained easily, the higher density will be required.

Materials used for subbase courses will be compacted to at least 100 percent of FAA T-611 maximum density. Where it can be shown that a higher density can be obtained easily, the higher density will be required.

The subgrade is a cohesive material and the top 6 in. will therefore be compacted to 90 percent of FAA T-611 maximum density.

RIGID PAVEMENT DESIGN

THICKNESS REQUIREMENTS

Thickness design curves were developed for rigid pavements to be used by light aircraft. Use was made of Westergaard's equations to calculate edge stress. These equations do not consider the effects of load repetitions, which were introduced into the development of the design curves through use of a design factor (defined as a ratio of flexural strength to edge stress). A curve relating design factor to repetitions was developed from the results of full-scale traffic tests.[5]

DESIGN PARAMETERS

The design criteria presented herein for rigid pavements involve several significant parameters. These are load, load distribution, load repetitions, soil strength, thickness, and concrete flexural strength. These parameters, except flexural strength, were discussed in connection with flexible pavement design. The discussions on load, load distribution, and load repetitions are also applicable to rigid pavement design and will not be discussed here. The other parameters as applicable to rigid pavement design are discussed below.

STRENGTH

Strength considerations include resisting stresses applied to the foundation by the loaded slab. The strength of foundation in regard to its resistance to stress is assessed by use of the plate bearing test to determine a modulus of subgrade reaction. Stress can be controlled by increasing the strength of the soil layer supporting the pavement slab or by increasing the thickness of the slab.

THICKNESS

The thickness of the rigid pavement slab is the parameter which controls the stress applied to the foundation. For a given loading

condition, an increase in thickness reduces the stress and a reduction in thickness increases the stress.

CONCRETE FLEXURAL STRENGTH

The design of rigid pavements for airfields is based upon the critical tensile stresses produced by the aircraft loads. The ability of the pavement to withstand these stresses is, in turn, determined by the strength of the concrete.

DEVELOPMENT OF DESIGN CURVES

The procedures used to develop thickness design curves made use of the Westergaard Analysis. This analysis assumes that the slab is a semi-infinite (one free edge), elastic, homogeneous, isotropic plate of uniform thickness supported on a dense liquid. Calculations and tests have indicated that the stresses produced by loading near a joint are equal to or greater than stresses produced by loading in the interior of a slab. The edge-loaded condition is the basis for this design method. However, in practice, some of the stress is transferred to the adjacent slabs. The stress along joints is therefore less than the free edge stress but still larger than the stress resulting from a load in the slab interior. Load transfer devices commonly used are keys or dowels or aggregate interlocks that develop from a crack through the concrete thickness, such as at weakened-plane (dummy groove) joints. Another method used is to thicken the slab along joints to resist the higher stresses. Laboratory model tests and prototype aircraft loading tests in the field have been employed to determine the amount of stress relief that is accomplished by transfer of stress from the loaded slab to the adjacent unloaded slab through the stress relief mechanisms. Under normal conditions, it has been found that the stress relief can vary from a maximum of nearly 50 percent to a minimum of 25 percent. This value varies depending upon such factors as the joint opening, subgrade strength, warping and curling within the slabs, degree of distress in the slabs, and condition of the stress relief device constructed in the pavement; however, longtime performance studies have

indicated that 25 percent is a reasonable value. Therefore, when the edge stress due to a load tangent to a joint having a stress relief mechanism is computed, the computed stress is reduced by 25 percent

Westergaard's equation for calculating free-edge stress is as follows:

$$\sigma_e = \frac{3(1+\nu)P}{\pi(3+\nu)h^2}\left[\ln \frac{Eh^3}{100k\left(\frac{a+b}{2}\right)^4} + 1.84 - \frac{4}{3}\nu + (1+\nu)\frac{a-b}{a+b} + 2(1-\nu)\frac{ab}{(a+b)^2} + 1.18\,(1-2\nu)\frac{b}{\ell}\right] \tag{2}$$

where

σ_e = free-edge stress due to a single wheel tangent to the edge, psi

ν = Poisson's ratio of concrete

P = wheel load, lb

h = thickness of the slab, in.

E = modulus of elasticity of concrete, psi

k = modulus of soil reaction, psi/in.

a,b = semimajor and semiminor axes, respectively, of the elliptical contact area, in.

ℓ = radius of relative stiffness, in., where

$$\ell = \sqrt[4]{\frac{Eh^3}{12(1-\nu^2)k}} \tag{3}$$

For multiple-wheel gears, the equations developed by Westergaard become rather complex. A graphical solution of these equations in the form of influence charts was developed by Pickett and Ray.[6] Current practice employs results from these influence charts for multiple-wheel assemblies.

The calculated edge stress, concrete flexural strength, and load repetitions are related by a design factor. The design factor is defined

as the ratio of concrete flexural strength to the maximum edge stress, with allowances made for stress relief across joints. For 5000 coverages, the design factor is 1.3. The thickness corresponding to the stress for 5000 coverages of traffic can then be adjusted for other traffic levels through use of a ratio of actual thickness to standard thickness, H-ratio, as shown in Figure 5. This procedure is used in lieu of applying a different design factor for each coverage level. Curves of design factor versus coverages are available but computations are simplified if the described procedure is used.

The H-ratio versus traffic volume relationship for the initial crack condition is shown in Figure 5. In this figure, the traffic volume is expressed in terms of coverages, where 1 coverage is defined as the condition in which each point in the selected traffic area width has been subjected to a maximum stress repetition by the gear in question. Since aircraft gears are composed of a variety of combinations of wheels, wheel sizes, wheel spacings, and arrangements of the wheels and gears, the traffic volume (number of aircraft departures) represented by any given coverage level is variable, depending upon the aircraft gear configuration. Coverages can be converted to aircraft departures by the use of a departure-per-coverage (pass-per-coverage) ratio that is constant for any given aircraft. For this study, a departure-per-coverage ratio of 7.94 was used for the single-wheel gear aircraft and 5.2 for the dual-wheel gear aircraft.

The above criteria were used to develop the thickness design curves shown in Figures 6 and 7. Use of these curves to determine slab thickness requires entering the curves with the concrete flexural strength, moving horizontally to the modulus of soil reaction, (k) , vertically to the aircraft gross weight, horizontally to the departure level, and then vertically to the thickness scale.

MINIMUM THICKNESS

Although the rigid pavement design procedure allows the selection of a pavement thickness as low as 4 in., it is deemed wise to designate minimum thickness values. Minimum thicknesses are necessary to provide

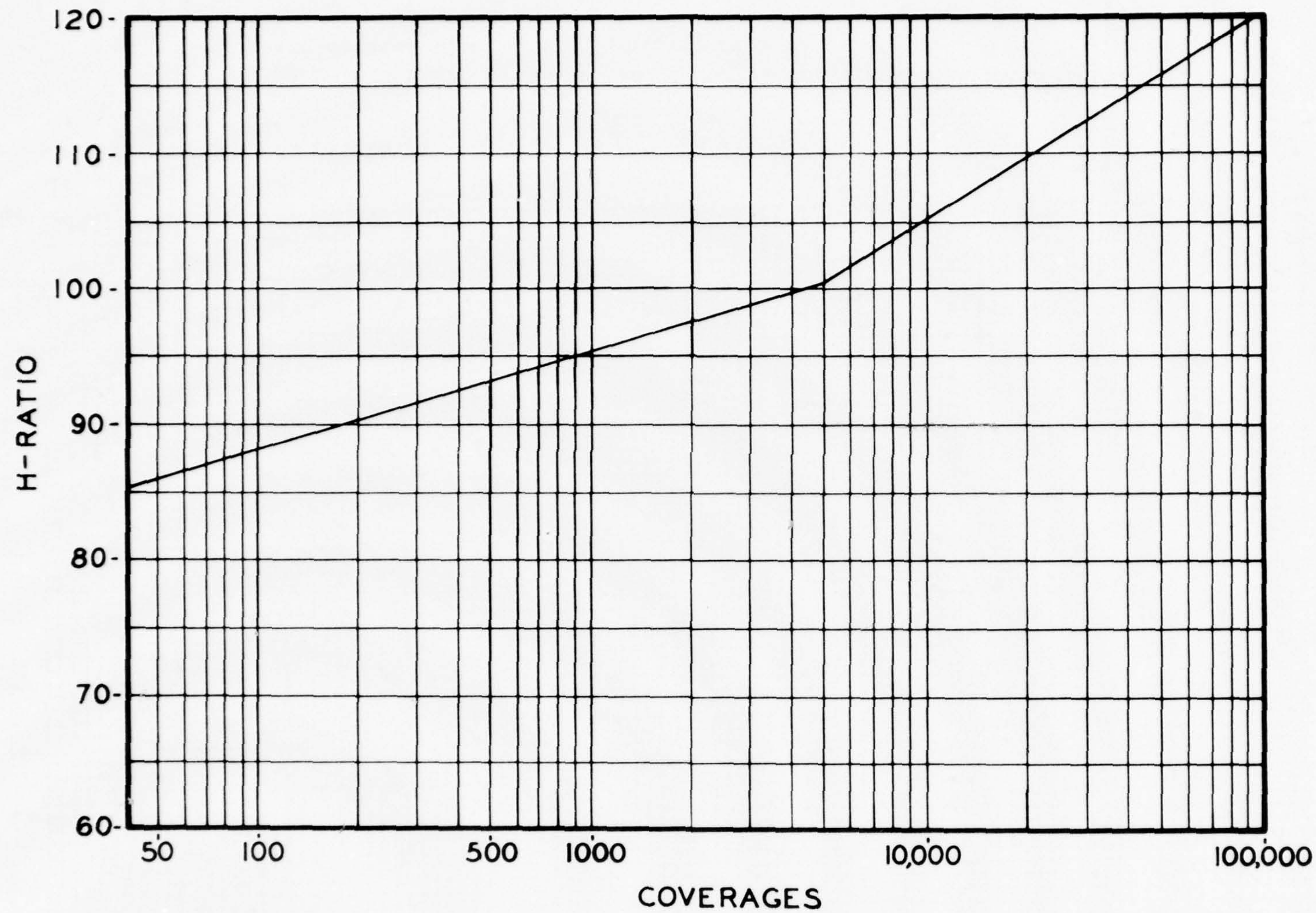
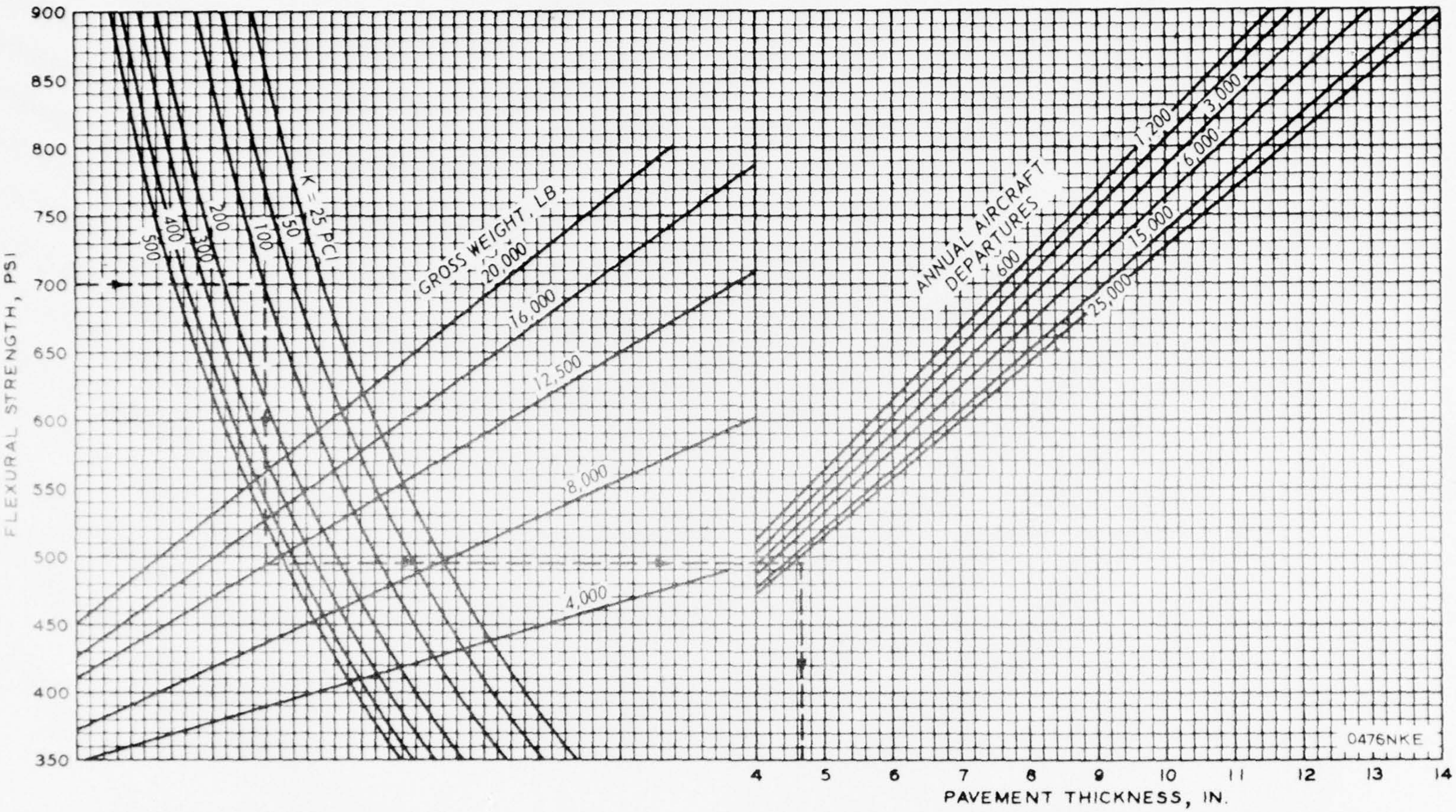
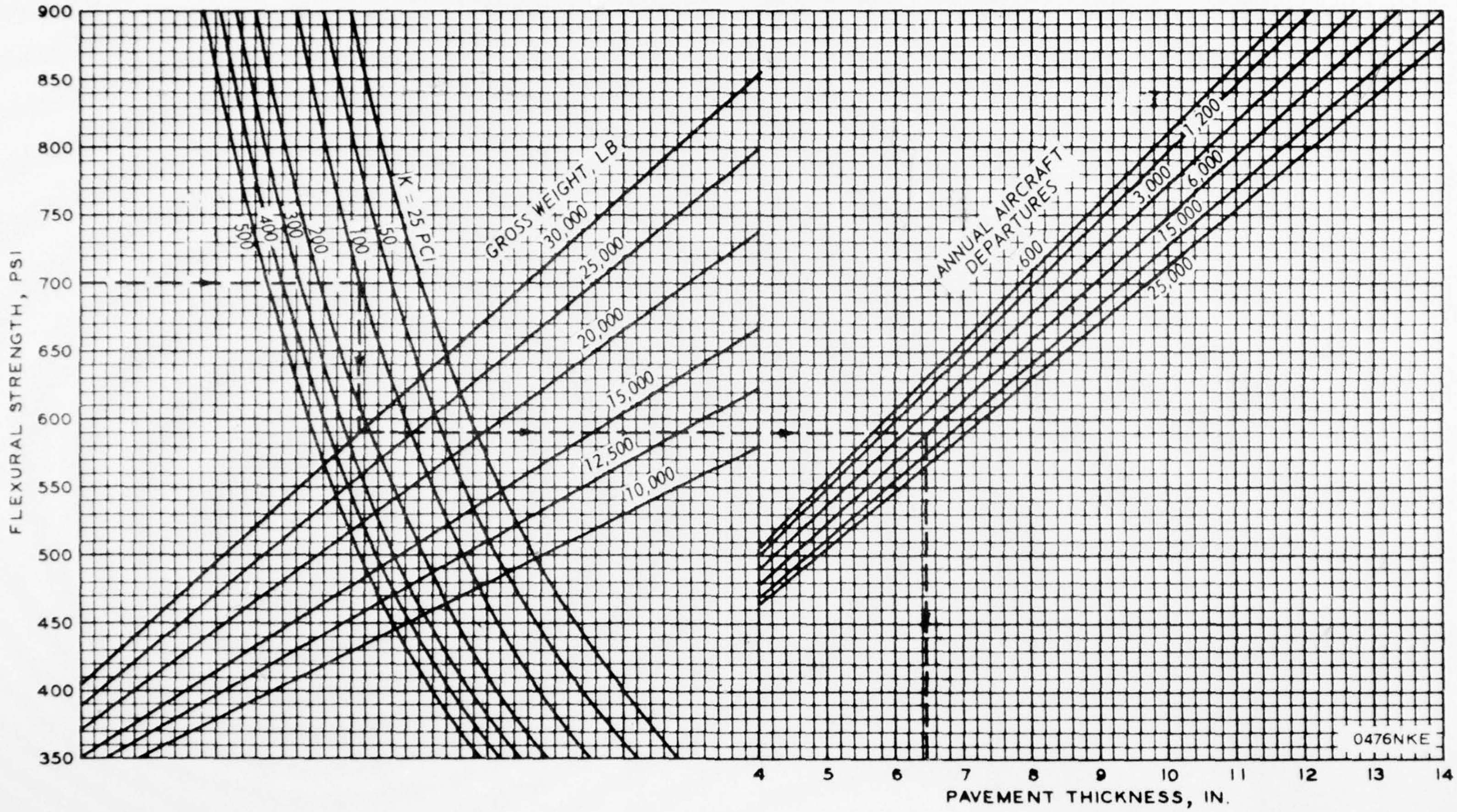


Figure 5. H-ratio versus coverages



NOTE: CURVES BASED ON 20-YEAR PAVEMENT LIFE.

Figure 6. Rigid pavement design curves for light-load aircraft, single-wheel gear



NOTE: CURVES BASED ON 20-YEAR PAVEMENT LIFE.

Figure 7. Rigid pavement design curves for light-load aircraft, dual-wheel gear

for several unknowns, such as heavy vehicle loads (such as fuel or service vehicles) which may occasionally use the pavement, climatic effects, and lack of experience with exceptionally thin pavements. It is therefore recommended that nonreinforced portland cement concrete (PCC) pavements have a minimum thickness of 5 in. and that reinforced PCC pavements have a minimum thickness of 4 in. when containing at least 0.05 percent steel.

JOINT REQUIREMENTS

Joints for use in pavements for light aircraft will conform to the requirements set forth in AC 150/5320-6B, with the following exceptions or additions:

- a. The spacing of joints for 5-in. PCC nonreinforced pavements will be 12.5 ft for longitudinal joints and 15 ft for transverse joints. For 5-in. reinforced PCC pavements with a minimum of 0.06 percent steel, the spacing will be a maximum of 30 ft. For 4-in. reinforced pavements, the maximum spacing will be 12.5 ft for longitudinal joints and 20 ft for transverse joints.
- b. Dowels for 4- to 5-in. pavements will be 5/8 in. in diameter, 12 in. long, and spaced 12 in. center to center.

CONSTRUCTION

The use of rigid pavement for light aircraft will depend, to a large extent, on the cost of the pavement relative to other pavement types. The cost of thin rigid pavements will depend to a greater extent on construction cost rather than material cost. The in-place cost of PCC in terms of unit surface area per unit thickness is certainly not a linear function of slab thickness but, in terms of, say, square yards of surface area per inch of thickness, will increase as thickness decreases. This will be due to the increased influence of such costs as finishing, curing, and equipment which remain constant no matter what the thickness, while material cost may decrease as a linear function of thickness. In addition to cost, construction of thin pavements presents a number of unique problems. For these reasons, guidance for constructing thin PCC pavements is presented in Appendix A.

SOIL STABILIZATION

There are basically three types of soil stabilization: mechanical, chemical, and bituminous. These types of stabilization are used to improve the strength of a soil to make it more suitable for use as part of a pavement structure. Stabilized soils are not generally intended to serve as surface course because of the effects of weathering and the abrasive actions of tires. However, in lightly trafficked areas such as hangar floors or some parking areas they may be considered for such a use. The normal procedure is to provide a surface course in order to resist the abrasive action of traffic and weathering.

MECHANICAL STABILIZATION

Mechanical stabilization produces, by compaction, an interlocking of soil aggregate particles and may develop to some extent a cementing action in the fine soil particles. The strength of a mechanically stabilized soil depends mainly upon the inherent strength of the graded mixture. Therefore, when a very stable soil is required, it is important that the grading of the soil-aggregate mixture be such as to produce a dense mass when compacted. When a high bearing capacity is required and suitable natural, well-graded soils are not available, the required gradation may be obtained by processing the soils to remove undesirable fractions or by blending two or more soils in the proper proportions. The blending of soils for use as a base or subbase must meet the requirements for base or subbase material.

CHEMICAL AND BITUMINOUS STABILIZATION

Chemical or bituminous stabilization is used when it is desired to change properties of a soil in order to provide a satisfactory construction material or improve soil conditions. Chemical or bituminous stabilization is generally used to accomplish one of the following objectives:

a. To provide a "working platform."

b. To modify soil properties such as the plasticity index.

c. To upgrade soils and soil-aggregate mixtures by increasing strength and durability.

If the objective of stabilization is to provide a working platform during construction operations, only enough chemical additive is used to obtain a hardened mass for temporary use. Similarly, if modification of certain properties of a soil is desired, the quantity of stabilizer to be used is the minimum amount required to obtain the desired result. Stabilization of a soil for the purpose of permanently upgrading the quality of the material generally involves the use of higher percentages of admixture. However, as with other stabilization objectives, no more than the minimum amount of chemical required to achieve the desired result should be used. Reference 7 may be used to determine the amount and type of stabilizer required.

THICKNESS DESIGN OF FLEXIBLE PAVEMENTS UTILIZING STABILIZED LAYERS

The use of stabilized soil layers within a flexible pavement provides the opportunity to use marginal materials; i.e., materials that do not meet the specifications, for base and subbase courses. When stabilization is used to simply upgrade a soil for use in a pavement structure, the thickness requirements will be the same as for a conventional flexible pavement. Some soils when stabilized may be used to reduce the overall thickness of a flexible pavement through the use of equivalency factors[8] shown in Table 2, provided they meet strength and durability requirements. This table relates the soil, and its equivalency factor, to the type of stabilizing agent used and the layer for which the stabilized soil would normally be used. The procedure for utilizing the equivalency factors in designing a pavement with stabilized layers is to design a conventional flexible pavement for the design conditions and then to convert that conventional section into an equivalent stabilized section.

USE OF EQUIVALENCY FACTORS

Table 2 lists recommended equivalency factors. The table shows factors for base courses and subbase courses. The individual factors

Table 2

Equivalency Factors

Material	Equivalency Factors Base	Equivalency Factors Subbase
Asphalt-stabilized		
All-bituminous concrete	1.15	2.30
GW, GP, GM, GC	1.00	2.00
SW, SP, SM, SC	--*	1.50
Cement-stabilized		
GW, GP, SW, SP	1.15	2.30
GC, GM	1.00	2.00
ML, MH, CL, CH	--*	1.70
SC, SM	--*	1.50
Lime-stabilized		
ML, MH, CL, CH	--*	1.00
SC, SM, GC, GM	--*	1.10
Lime, cement, fly ash stabilized		
ML, MH, CL, CH	--*	1.30
SC, SM, GC, GM	--*	1.40
Unbound crushed stone	1.00	2.00

* Not recommended for use as base course (from Reference 8).

represent the number of inches of base on subbase which can be replaced by 1 in. of stabilized material. For example, the subbase equivalency factor for cement-stabilized GW soil is 2.3 which means that 1 in. of the stabilized GW soil will replace 2.3 in. of conventional unbound subbase material.

To design a flexible pavement with stabilized layers requires that a conventional flexible pavement be designed and then the layer or layers to be stabilized converted to the equivalent thickness of stabilized material. This is accomplished by dividing the thickness of unbound material by the equivalency factor.

For example, assume that a conventional flexible pavement has been designed that consists of 2 in. of asphaltic concrete, 6 in. of crushed stone base, and 10 in. of a gravel subbase. It is desired to use cement-stabilized GC in place of the base and subbase material. From Table 2, the equivalency factors for cement-stabilized GC are 1.0 for base courses and 2.0 for subbases. The 6-in. thickness of conventional base is divided by the equivalency factor of 1.0 indicating that 6 in. of cement-stabilized GC is required to replace the base course. The 10 in. of subbase is divided by the equivalency factor of 2.0 indicating that 5 in. of cement-stabilized GC is required to replace the subbase. The final section would then consist of 2 in. of asphaltic concrete and 11 in. of cement-stabilized GC soil.

THICKNESS DESIGN OF RIGID PAVEMENTS UTILIZING STABILIZED LAYERS

The use of stabilized soil layers under a rigid pavement provides the opportunity to upgrade the strength and quality of the foundation for the rigid pavement and thereby reduce the required slab thickness. The FAA has developed a procedure for designing rigid pavements on stabilized soils and this procedure is presented in AC 150/5320-6B. This procedure may also be used for light aircraft. However, rigid pavements for light aircraft are relatively thin and the thicknesses may not be reduced to any great extent. Therefore, for light aircraft pavements, substitution ratios have been developed which will simplify

the design. When placing a rigid pavement slab on a stabilized granular soil, the designer may reduce the slab thickness 1.0 in. for each 3.0 in. of stabilized material. When placing a rigid pavement slab on a stabilized fine-grained soil, the designer may reduce the slab thickness 1.0 in. for each 4.0 in. of stabilized material. Although the slab thickness may be reduced due to the use of stabilization, the slab thickness must meet the minimum thickness values.

MEMBRANE-ENCAPSULATED SOIL LAYERS FOR AIRFIELD CONSTRUCTION

GENERAL

For several years, the U. S. Army Engineer Waterways Experiment Station has been conducting a series of research and development projects aimed at finding a means for making use of fine-grained soils in their natural state as a base or subbase course in highway and airport pavements. As a result, a method was developed which involves encapsulating soil layers in membranes.

Fine-grained soils, compacted to a high density at an appropriate water content, can obtain a high bearing capacity. However, these soils are water-susceptible, and if they absorb water, their density and bearing capacity will drop to very low values. This instability of fine-grained soils in the presence of water does not allow them to be used in pavement structures in their natural state, unless they are made waterproof.

Experience has demonstrated that the concept of encapsulating a soil layer in a waterproof membrane is feasible, and that this soil layer may be used in pavement structures. A method of constructing membrane-encapsulated soil layers (MESL) has been developed and the effectiveness of MESL in pavement structures has been demonstrated in several full-scale tests. Research described in References 9-11 indicates that MESL has performed as well as or better than higher strength conventional soil layers in pavements.

DEFINITION

A MESL layer is basically composed of fine-grained soil compacted to a high density at optimum or slightly below optimum water content. The soil is enveloped in two sheets of membrane and in order to maintain the water content is bonded at the edges by asphaltic material. The membrane prevents the intrusion of water, even when the adjacent soil is saturated or under flood conditions. Figure 8 shows a typical cross section of MESL replacing both the base and/or subbase courses in a flexible or rigid pavement.

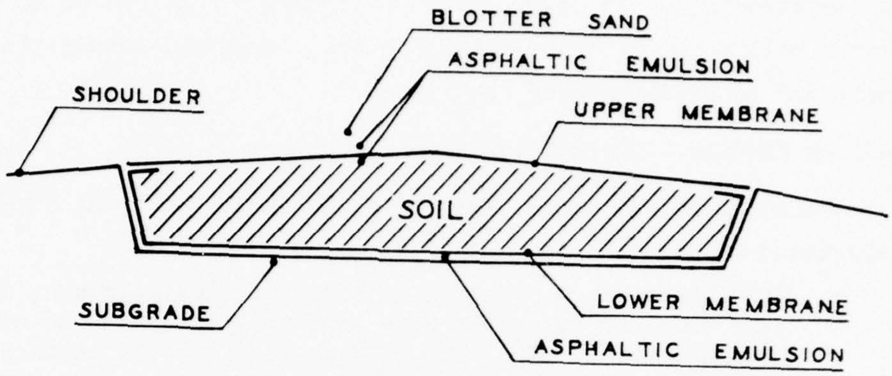


Figure 8. Typical MESL cross section

POSSIBLE USES

MESL may be used as a single layer in lieu of the base and subbase courses in a conventional flexible pavement. It may also replace only the base or subbase. In rigid pavements, MESL can be used as a base course in order to improve the modulus of soil reaction under the slab. MESL may also be used as a strengthening layer for unsurfaced airfields. The MESL surface can withstand the abrasive action of tires, although extra care is needed in maintenance.

The use of MESL is suggested for places where granular materials, meeting conventional pavement requirements, are not available or when transportation costs are high. The decision to use conventional pavement or MESL must be based on a comparative study, from the viewpoints of economy, maintenance, and construction capabilities.

The great advantage of the MESL system lies in the possibility of using the local fine-grained soils as base course material which may result in significant cost savings. It is known that the transportation of base course material from far sources is one of the most expensive items in pavement construction, and use of MESL could reduce or eliminate this cost.

Disadvantages of this system are the need for increased manpower and the difficulty of preventing tears or punctures in the membrane during construction. It is important to remember that a hole in the membranes will allow water to enter the soil layer and reduce its strength and stability around that point.

SUMMARY OF CONSTRUCTION PROCEDURES

A summary of the procedures to follow in constructing a MESL are discussed below:[12-14]

a. MESL bed will be prepared according to design grade, at the same time and using the same earthwork equipment as used in cuts and fills. The MESL bed includes the compacted subgrade and the inside slopes of adjacent shoulders, where lower membranes will lie. The sketch shown in Figure 9 gives an

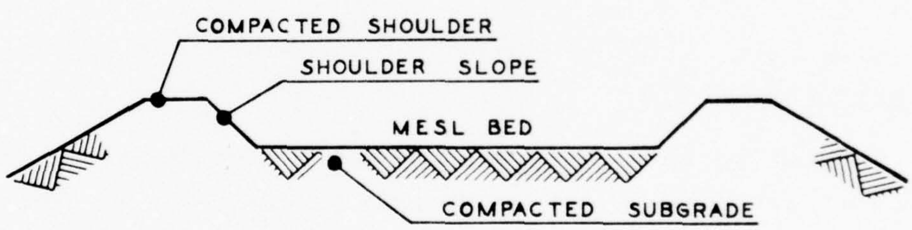


Figure 9. A MESL bed

example of a MESL bed. In fills, when the design grade for the bottom of the MESL is reached, shoulder construction will begin. In cuts, the soil is excavated to the top of the shoulder, then only the area to contain the MESL will be excavated. Shoulders are essential for protecting the lower membrane throughout the design life; therefore, it is good practice to protect the shoulders from erosion. Compaction should be applied on the subgrade as in conventional pavement, in order to obtain adequate densities. A MESL bed must contain no loose stones or other materials that can endanger membrane integrity.

b. Spread asphalt emulsion on the bottom and sides of the MESL bed, at a rate of 0.2 to 0.3 gal per sq yd, in order to bond the membrane to the subgrade and avoid displacement during construction. Residual asphalt that does not penetrate the subgrade also serves to seal small punctures in the membrane.

c. The lower membrane is then placed over the emulsion. Any overlap between two membranes at the bottom and edges must be from 1 to 2 ft and bonded with a light application of asphalt emulsion. The lower membrane must be long enough to provide at least a 2-ft overlap of the upper membrane.

d. The total soil layer to be encapsulated must be composed of compacted layers of material each 6 in. or less in thickness. Natural soil from the construction site or from nearby borrow areas that meets design criteria and material requirements may be used. The soil must be at the proper moisture content before placing on the membrane. Therefore, it is suggested that a pugmill or rotary mixer be used to work the soil for efficient operations and to obtain a homogeneous material. A 6-mil polyethylene membrane, without protection, will not withstand traffic of construction equipment and loaded dump trucks. Therefore, the first layer of soil must be placed before any equipment can operate over the membrane. This first layer may be placed with front-end loaders working from both sides and using a dozer to push soil ahead, or, perhaps a better procedure is to use dump trucks with tailgate spreaders moving backward, as is done in construction of asphalt surface treatments. Using these methods the soil is always applied ahead of the truck passage and covers the membrane before wheels pass over it. Compaction must then be applied, preferably with rubber-tired rollers. The MESL must be constructed so that the finished pavement surface will have the same grade as the adjacent shoulders, in order to provide complete protection for the lower membrane and to allow rainwater to run off freely.

e. After the complete soil layer has been compacted and graded, an asphalt emulsion is placed on the edges of the soil layer at a rate of 0.2 to 0.3 gal per sq yd and the excess lower membrane folded over the edges of the MESL layer. Asphalt emulsion is then spread at the above rate on the entire surface of the compacted layer, including the portion covered by the lower membrane at the edges. This asphalt will bond the upper membrane to the soil and seal the joint between the upper and lower membranes. The compacted soil surface must be cleaned before spreading asphalt and contain no material that can puncture the membrane.

f. The next step, which could be done simultaneously with spreading of the asphalt, is to place the upper membrane. A special and simple apparatus can be attached to the rear of an asphalt distributor to unroll the membrane after spraying of emulsion and before curing.

g. In order to complete the asphalt-polypropylene-asphalt system and provide a waterproof coat over the compacted soil layer, an emulsion film will be applied at the rate of 0.2 gal per sq yd on the upper membrane.

h. Finally, a thin layer of fine sand will be applied over the emulsion, before its curing, and then compacted with a rubber-tired roller. The excess sand will be removed by sweeping. The sand works as a blotter for the excess asphalt and improves friction and eliminates lubricating effect between the MESL and surface course.

DESIGN CRITERIA AND MATERIAL REQUIREMENTS

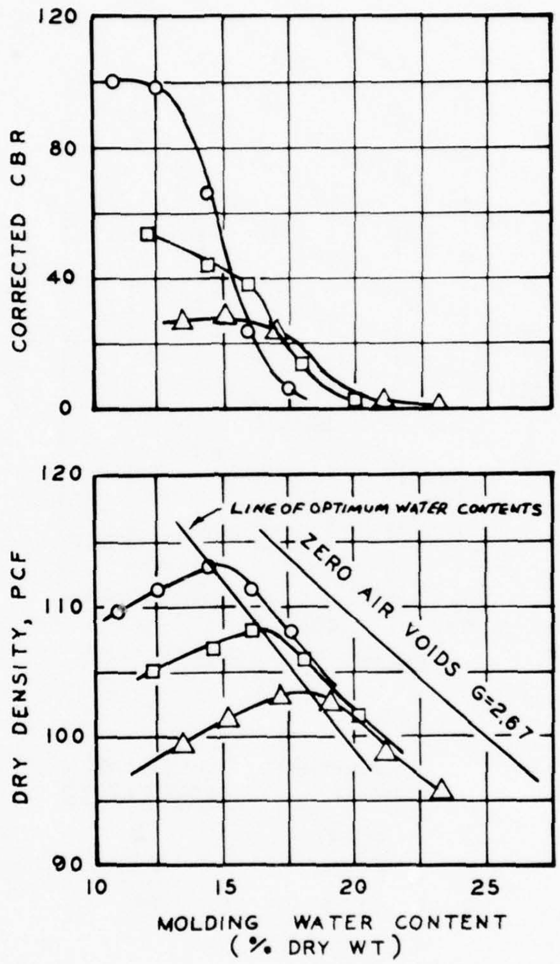
As a result of full-scale tests, material requirements and design criteria have been established for the construction of MESL.

FLEXIBLE PAVEMENTS

a. Soil classification. Soils to be used in MESL system should be fine-grained soils, with more than 50 percent passing the No. 200 sieve, and classified as CL or CH according to Unified Soil Classification System.[15] CL soils are usually lean clay or sandy clay and, among the fine-grained soils, they have the best compaction characteristics. CH soils also perform well, although they consolidate more than the CL soils. Both CL and CH may contain gravel, sand, or silt. Fine-grained soils such as ML and MH have not been sufficiently tested for MESL purposes. Further research must be conducted before these soils may be considered suitable. However, it is known that MH soils have poor compaction characteristics, and ML soils have a very narrow range of moisture content for effective compaction. Even if these materials are considered acceptable for MESL construction, close field control will be needed. It should be remembered that, if field compaction does not obtain the specified density, it is difficult to evacuate the MESL, in order to correct moisture content and recompact, without damaging the membrane. Organic soils are not suitable for MESL construction.

b. Laboratory tests. Moisture-density relationships according to MIL-STD-621A, Method 100,[16] must be determined. Curves for compaction efforts CE 12, CE 26, and CE 55 should be drawn, as well as the corresponding unsoaked or as-molded CBR curves as shown in Figure 10. These data will be helpful in determining design requirements. Compaction efforts CE 12 and CE 55 approximate the compaction efforts of AASHO Methods T-99 and T-180, respectively.

c. Density and CBR requirements. The basic data needed to design a MESL are the dry density and CBR at optimum water content for CE 55 compaction effort. Therefore, data from Figure 10 may be used to plot Figure 11 based on CE 55 optimum water content. This curve then enables the designer to choose reasonable density and CBR values that should be obtained in the



LABORATORY COMPACTION:

	COMPACTION EFFORT	NUMBER OF BLOWS/LAYER
△	CE 12	12
□	CE 26	26
○	CE 55	55

Figure 10. Molding water content versus density and CBR for a lean clay soil

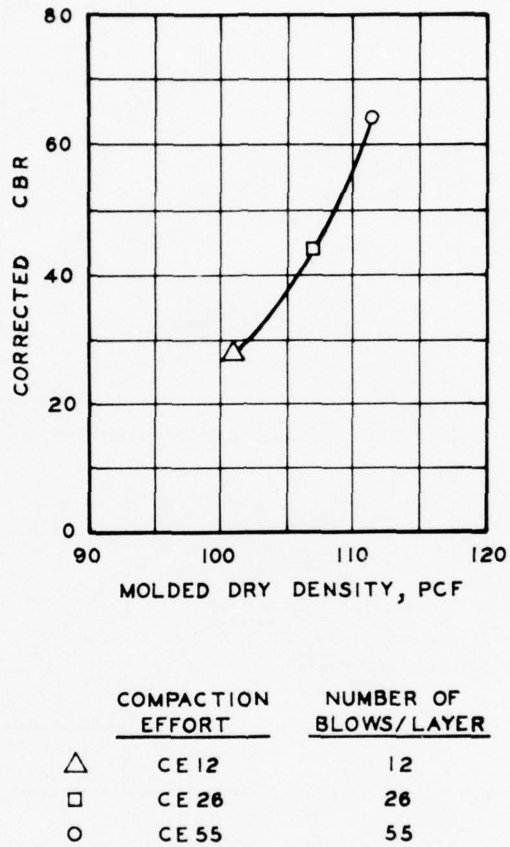


Figure 11. Molded dry density versus CBR for optimum water content

encapsulated soil layer to provide a good foundation for the pavement. This density, expressed in terms of percentage of CE 55 maximum density, will determine the design compaction effort. As an example, assume that a material with the characteristics shown in Figures 10 and 11 is available and that a 30-CBR MESL will provide a satisfactory foundation for an airfield pavement. By entering Figure 11 with the 30 CBR, the designer can select the corresponding density of 102 pcf, which is approximately 90 percent of the maximum dry density at optimum water content for CE 55 compaction effort. Then the specified density for this particular example to obtain the 30 CBR will be 90 percent of CE 55 maximum density. It is recommended that the density be specified between 90 percent and 95 percent of CE 55 maximum for airfields. Moisture content will be the optimum or slightly below optimum. A moisture content above optimum should not be used.

d. Thickness design. Full-scale accelerated traffic tests run at WES described in References 9-11 have indicated that MESL performs as well as or better than conventional base courses. However, tests have not yet determined the long-term performance of MESL. Therefore, the thickness of MESL should be determined using the conventional flexible pavement criteria.

RIGID PAVEMENTS

The requirements for soil and construction techniques are basically the same for MESL under rigid pavement as under flexible pavement.

Since the base course thickness influences the modulus of soil reaction under the slab and consequently the thickness of the slab, a base course thickness must be chosen that yields the most economical design. It is required that the MESL be at least 6 in. thick.

The modulus of soil reaction is determined according to the following procedure.

a. Plate bearing tests must be run on the subgrade, as prescribed in MIL-STD-621A, Method 104. The modulus value obtained from the test is then corrected for bending of the plate and for saturation of the soil, in order to obtain the subgrade modulus (k). This value is then used with Figure 12 which considers the thickness of the MESL base course and yields the effective k value on top of the MESL to be used in design.

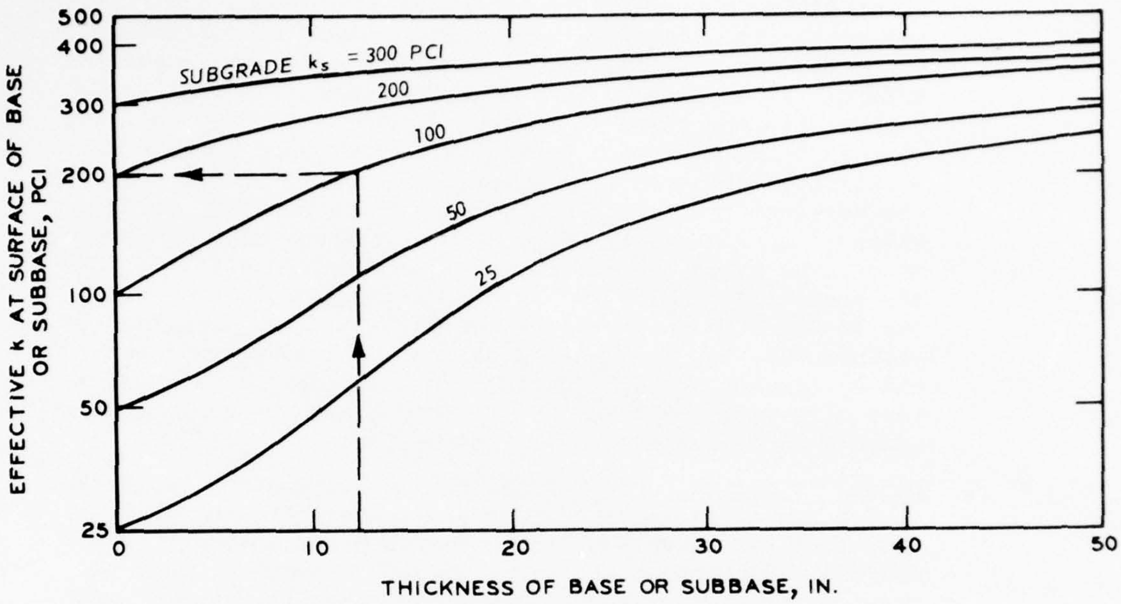


Figure 12. Effect of base or subbase thickness on modulus of subgrade reaction

b. A small test section may then be constructed on the subgrade soil, prior to the design of the pavement, in order to run the plate bearing test on the MESL surface. The k value to be assigned for design is the lesser of the two values determined using the above procedures. The maximum value allowed for k is 500 pci. The modulus of soil reaction so assigned may be used with the conventional design procedures for calculation of the concrete slab thickness.

MEMBRANES

LOWER MEMBRANE

For the lower membrane, a polyethylene sheet with a minimum thickness of 6 mils should be used. This material is available in sizes up to 40 by 100 ft.

UPPER MEMBRANE

Reference 9 describes the upper membrane as a polypropylene nonwoven fabric with the following properties:

a. Minimum tensile strength in either direction, 50 lb per in., tested according to ASTM Method D 1682-64.

b. Weight, 3 to 5 oz per sq yd.

c. Black in color to resist oxidation and hardening.

d. Easily saturated with emulsified asphalts.

BITUMINOUS MATERIAL

Emulsified asphalts may be ASTM grades CRS-2, RS-2, CSS-1h or SS-1h. Grades CRS-2 or RS-2 should be used in cold climates and CSS-1h and SS-1h in hot climates.

BLOTTER SAND

According to Reference 10, sand to be used as blotter sand must have at least 90 percent passing a No. 10 U. S. standard sieve and no more than 10 percent passing a No. 200 screen. The rate should be the minimum required to blot the excess asphalt.

DESIGN FOR COLD REGIONS

Adequate data to evaluate MESL performance in cold regions are not available. Tests performed at the U. S. Army Engineer Cold Regions Research and Engineering Laboratory, Hanover, N. H., have shown that, if MESL impermeability may be guaranteed, thereby ensuring a closed system, then freezing will cause much less heave than in an open system. Also, loss of bearing capacity due to thaw effects has been quite small. However, no definite information is available that allows MESL construction in cold regions.

EXPECTED LIFE OF A MESL

When MESL is used as a base course in flexible pavements, a plant-mixed bituminous surface course at least 2 in. thick is required. Loose stones could puncture the upper membrane; therefore, surface treatments are not allowed. The thickness of a rigid pavement slab over a MESL will be determined using the conventional design criteria discussed previously.

Rubber-tired trucks as well as conventional paving machines may operate over MESL before paving, without damage to the upper membrane.

The important requirement of a MESL system is to keep the soil layer waterproof. As long as this condition is satisfied, the pavement will perform well. According to available literature and limited field experience, a life of about 20 years may be expected for the membranes when they are underground or when coated with bitumen. Therefore, if a MESL pavement is well designed, constructed, and maintained it may be expected to match the life of the membrane.

b. Weight, 3 to 5 oz per sq yd.

c. Black in color to resist oxidation and hardening.

d. Easily saturated with emulsified asphalts.

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DESIGN OF UNSURFACED SOIL AREAS

Over the years, tests have been conducted to develop criteria for unsurfaced soil layers with the major emphasis being on expedient airfields for use by the military in the Theater of Operations. From these tests, criteria were developed that are applicable to roads, hardstands, airfields, etc., regardless of where they are located. The initial developments were directed at developing criteria for operation on the natural subgrade. This effort resulted in the development of a procedure for determining the strength of soil needed to support a given load. There were instances when the natural subgrade did not have sufficient strength to support a particular load, so that a soil or aggregate strengthening layer was required on top of the subgrade. The next area of development with respect to unsurfaced criteria was to develop criteria for determining the thickness of a strengthening layer required above the natural subgrade to support a load.

Unsurfaced soil areas may be used by all aircraft where the strength is sufficient. However, there are problems associated with these areas which must be considered. For instance, the soil will become soft when subjected to rainfall or freeze-thaw cycles. The use of a membrane on the surface will protect the soil from rainfall and allow it to be used in wet or dry weather. Another problem associated with unsurfaced areas is dust. Grass may be planted on the areas to help control dust, or dust control agents may be used.

DESIGN PARAMETERS

The parameters used in the design of unsurfaced soil areas for light aircraft are basically the same as those used in the design of a flexible pavement. These are load, load distribution, soil strength, traffic, and thickness.

LOAD

The load needed to design an unsurfaced area for light aircraft

is the tire load for a single-wheel gear aircraft and the ESWL for a dual-wheel gear aircraft.

LOAD DISTRIBUTION

Load distribution is concerned with the manner in which the load is transferred to the unsurfaced area. The important factors influencing the load distribution are number of tires, tire spacing, and tire pressure or contact area. For unsurfaced areas, the tire inflation pressure is used for normal calculations. When the average ground contact pressure is known, it should be used.

SOIL STRENGTH

The CBR is the soil strength parameter used in unsurfaced soil strength determinations. For unsurfaced soils, it is assumed that the soil strength will remain a constant value. Should the soil strength decrease, the unsurfaced area will have to be reevaluated.

THICKNESS

A thickness of higher strength soil is at times needed above the subgrade to upgrade the capability of an unsurfaced soil area, when the in situ soil does not have the strength needed to support the anticipated traffic.

TRAFFIC

The basic criteria were developed using traffic expressed in coverages. It was therefore necessary to convert aircraft departures to coverages through use of a departure-to-coverage ratio. The ratio used for the single-wheel gear was 7.94 and for the dual-wheel gear was 5.2.

STRENGTH REQUIREMENTS

A nomograph[17] which enables the designer to determine the strength of soil required to support a given loading condition is shown in Figure 13. This nomograph relates the tire pressure, load, soil strength, and traffic. The tire pressure is the actual inflation pressure, the

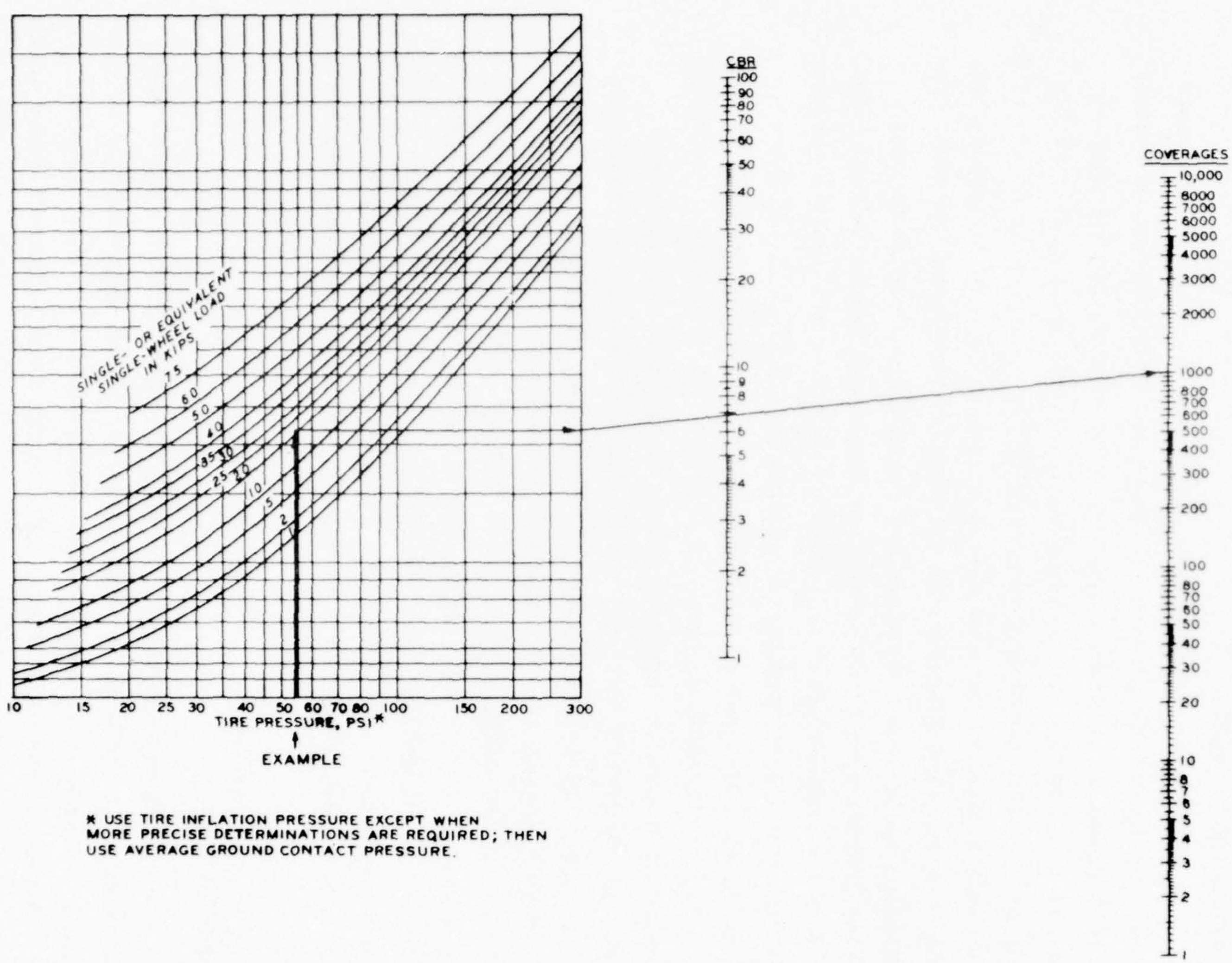


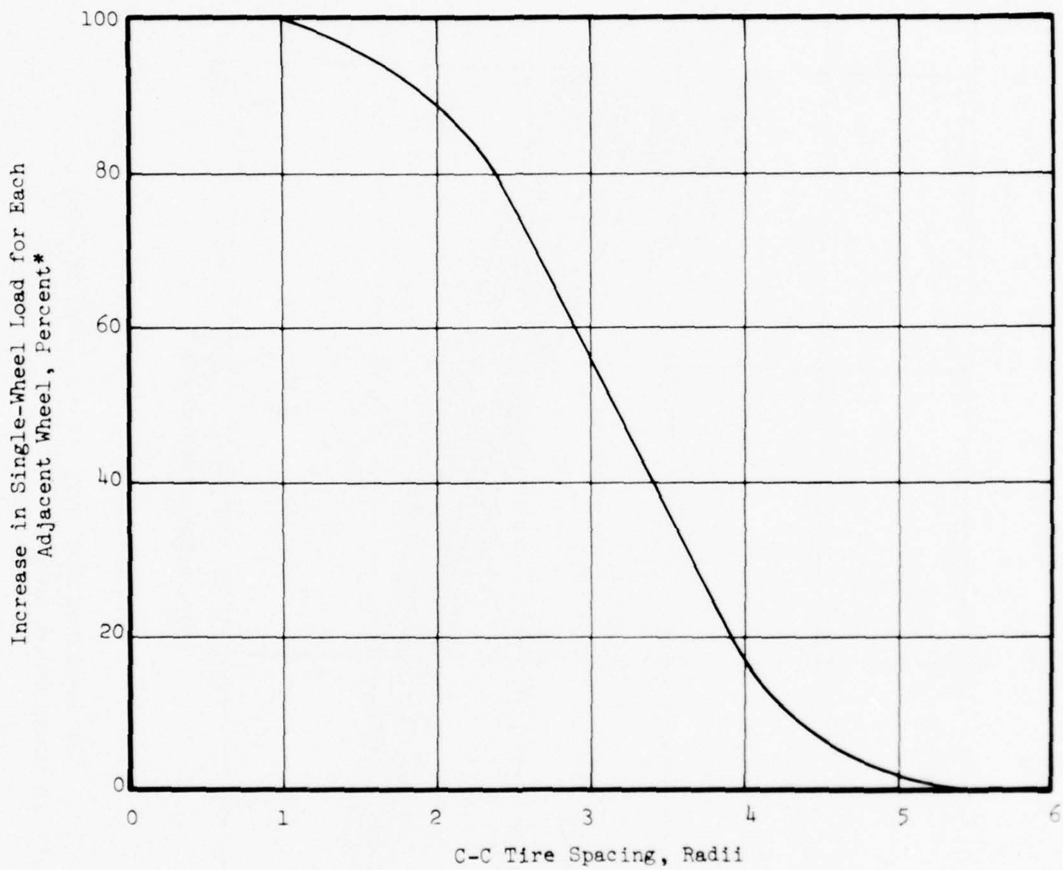
Figure 13. CBR required for operation of aircraft on unsurfaced soils

soil strength is the CBR, the traffic is measured in coverages, and the load is the SWL or ESWL.

The ESWL is determined by use of Figure 14. This figure shows tire spacing versus the percent influence one tire load has on another in a multiple-wheel configuration. The tire spacing is expressed in radii and is determined by dividing the tire spacing in inches by the radius of a circle having the same area as the contact area of one tire. The percent influence that one tire load has on another represents the amount that one tire load must be increased to determine the ESWL. As an example, assume that two tires are spaced 18 in. center to center, the tire contact area is 75 sq in., and the tire load is 5950 lb. The radius of the contact area is $\sqrt{\frac{75}{3.14}}$, or 4.9 in. The spacing between the tires in radii is then 18 in. divided by 4.9 in. = 3.67. From Figure 14, the influence of one tire load on the other is found to be 24.8 percent. The ESWL is then 5950 lb × 1.248 = 7430 lb . Using the nomograph in Figure 13, specific design curves have been prepared whereby an unsurfaced soil area can be designed to support light aircraft having single-wheel (Figure 15) or dual-wheel (Figure 16) gears. These curves present the soil strength required to support a given load for a given number of departures. These criteria were developed using existing procedures[17] which consist of the nomograph presented in Figure 13, in conjunction with the ESWL adjustment curve (Figure 14). Use and development of the criteria involve the same parameters used for flexible pavement, and the discussion presented there is applicable here.

DESIGN EXAMPLE FOR SOIL STRENGTH CRITERIA

To illustrate the use of the soil strength criteria, assume that an unsurfaced airfield is to be designed for 12,000 departures of an airplane having a gross weight of 20,000 lb and a dual-wheel loading gear. Enter the curves in Figure 16 with the 12,000 aircraft departures, move vertically to the 20,000-lb line, then horizontally to the CBR scale and read a value of 7.2. This indicates that a soil having a CBR



* Increase in load on a single wheel of a multiple-wheel gear to account for effects of adjacent wheels of the multiple-wheel gear in arriving at an equivalent single-wheel load.

Figure 14. ESWL adjustment curve for unsurfaced soils

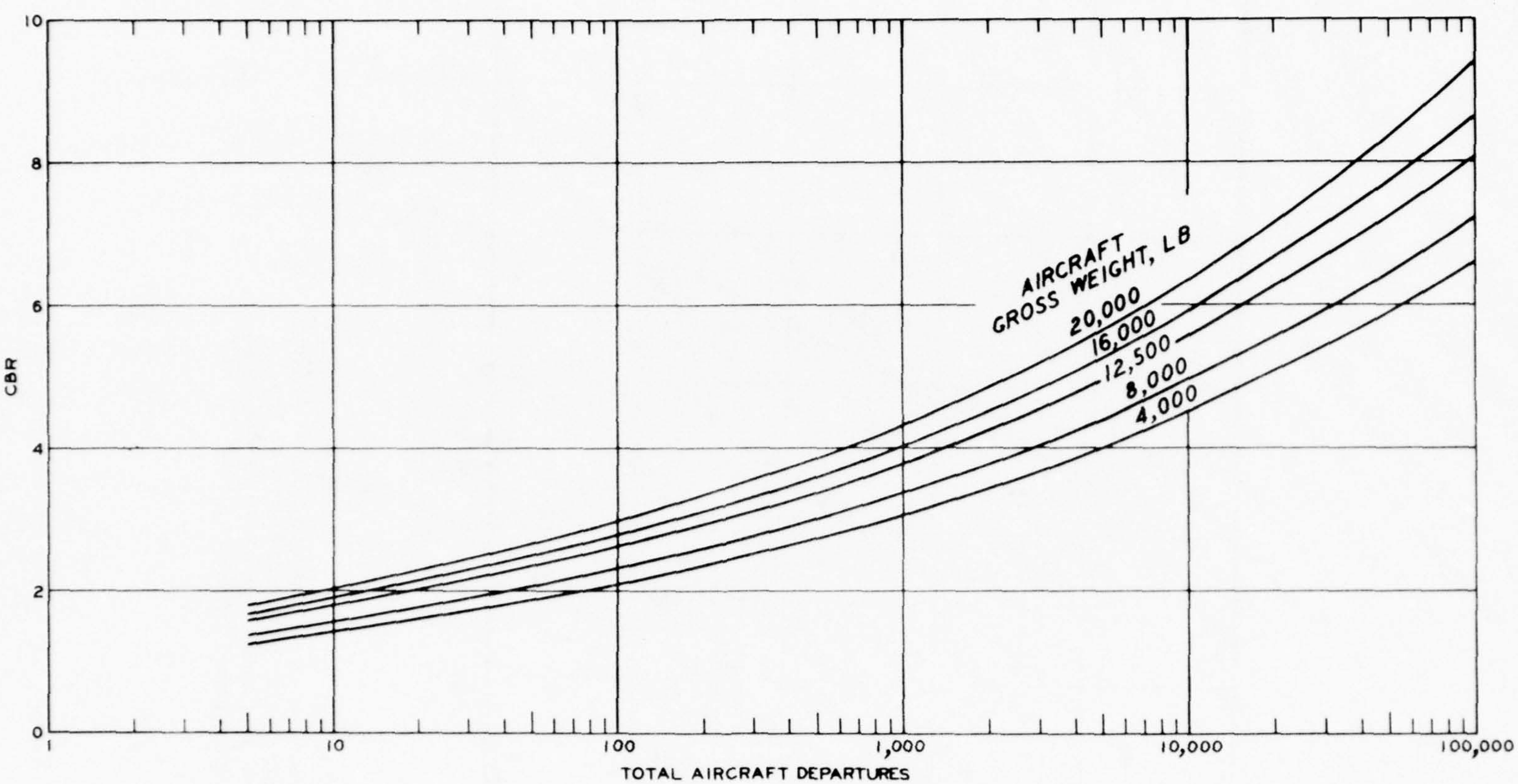


Figure 15. CBR required for supporting single-wheel aircraft on unsurfaced soils

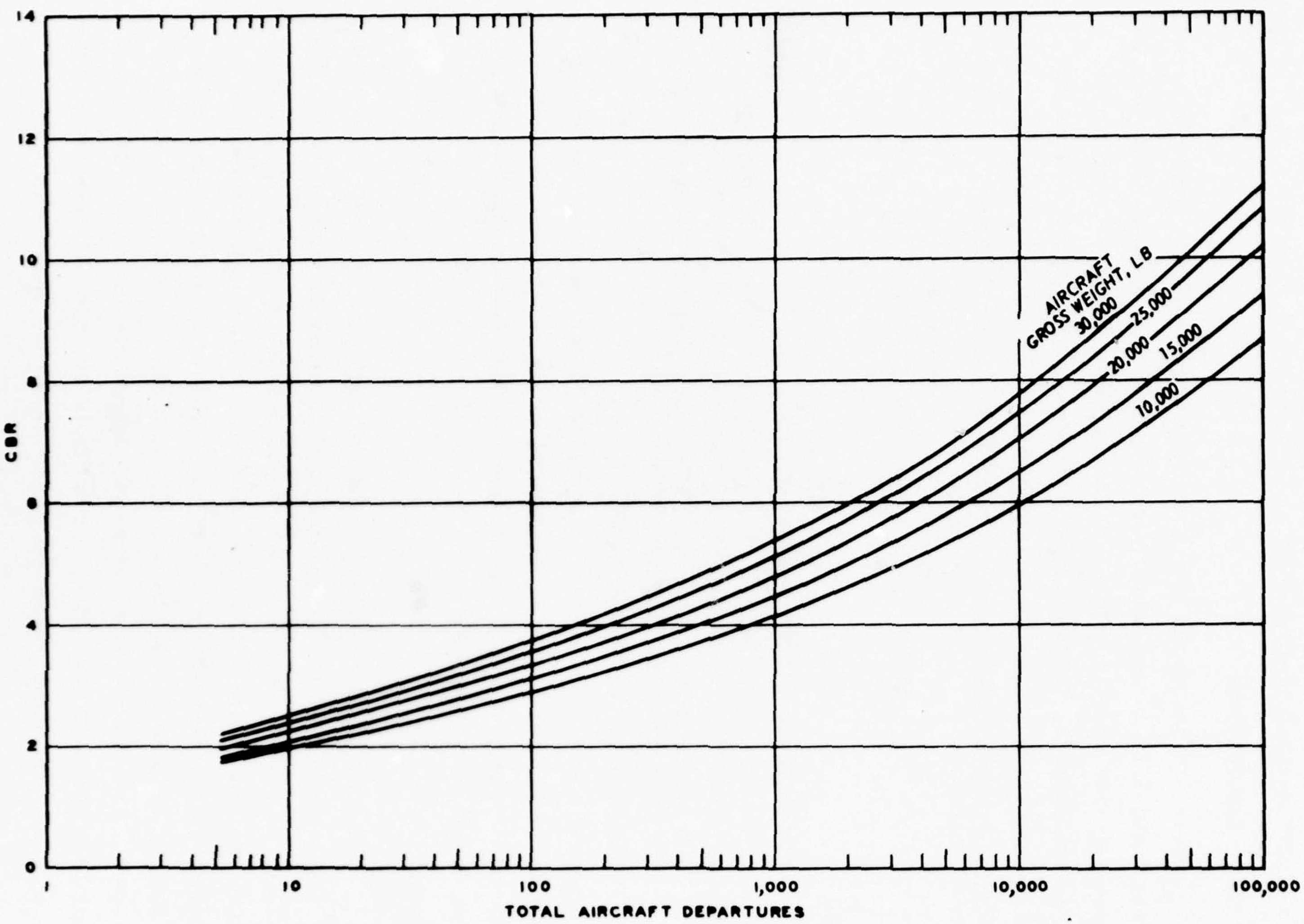


Figure 16. CBR required for supporting dual-wheel aircraft on unsurfaced soils

of 7.2 or greater will support 12,000 departures of a dual-wheel aircraft with a gross weight of 20,000 lb.

THICKNESS REQUIREMENTS

There are instances when a soil subgrade will not have the strength required to support the design traffic. In such instances, it is necessary to place a sufficient thickness of higher strength soil above the subgrade. A formula has been developed[18] which relates the design parameters so that the thickness of cover material required above a subgrade can be determined. This equation is as follows:

$$t = (0.176 \log C + 0.120) \sqrt{\frac{P}{8.1\ \text{CBR}} - \frac{A}{\pi}} \qquad (4)$$

where

- t = thickness of strengthening layer, in.
- C = traffic, coverages. The design departure level must be converted to coverages in order to use this equation
- P = SWL or ESWL, lb. This ESWL is the flexible pavement ESWL determined as shown in Reference 3
- A = tire contact area, sq in.

This equation was used to develop specific design curves to be used for determining the thickness on the strengthening layer required above a subgrade of given strength for the single- and dual-wheel aircraft. These curves are shown in Figures 17 and 18.

EXAMPLE

The above example illustrating the soil strength criteria indicated that a CBR of 7.2 was required in order to support 12,000 departures of a dual-wheel aircraft having a gross weight of 20,000 lb. Assume that an airfield is to be provided for this same aircraft at a location where the in-place CBR is 5.0. This will require some thickness of soil to be placed over the 5.0 CBR in order to support the design aircraft. The traffic level of 12,000 departures represents 600 annual departures for a 20-year life. From Figure 18, the thickness requirement for a 5 CBR, 600 annual departures, and 20,000 lb gross weight is

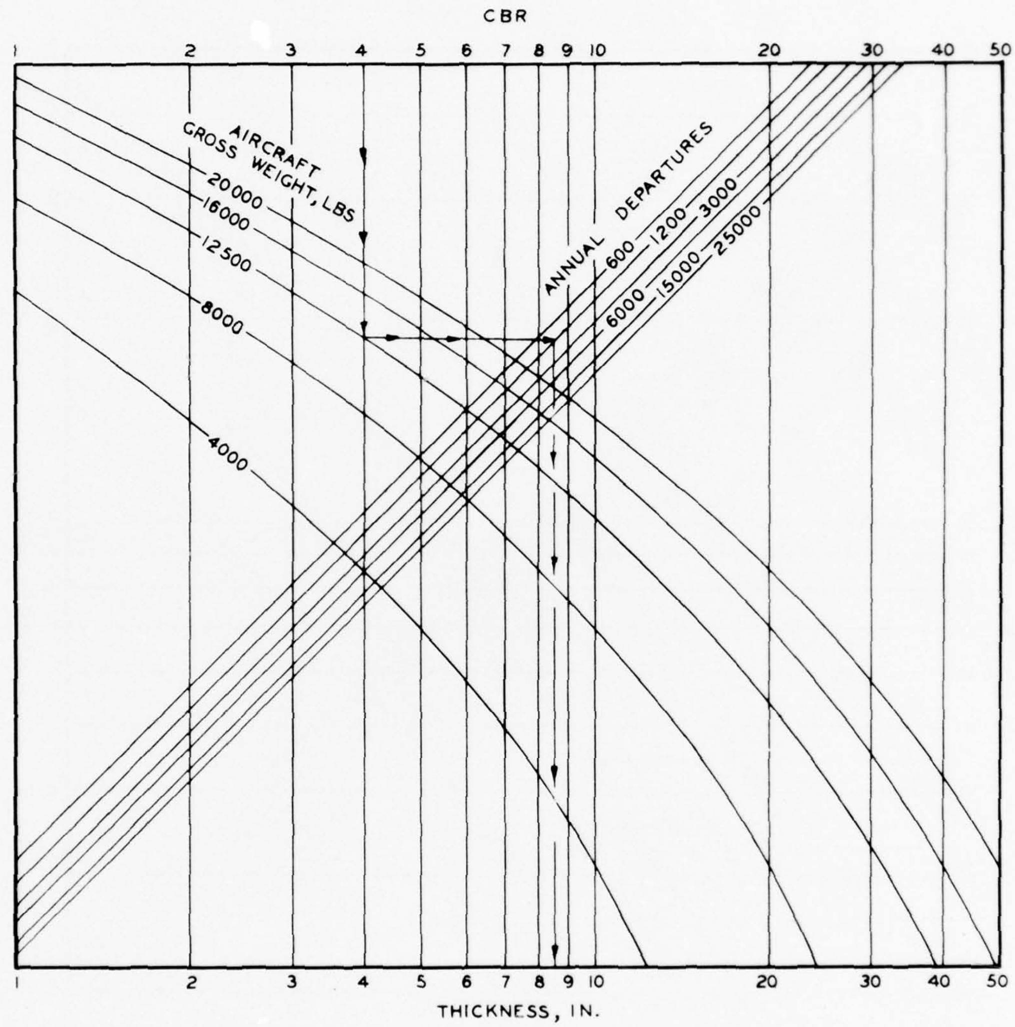


Figure 17. Unsurfaced soil thickness design for single-wheel gear

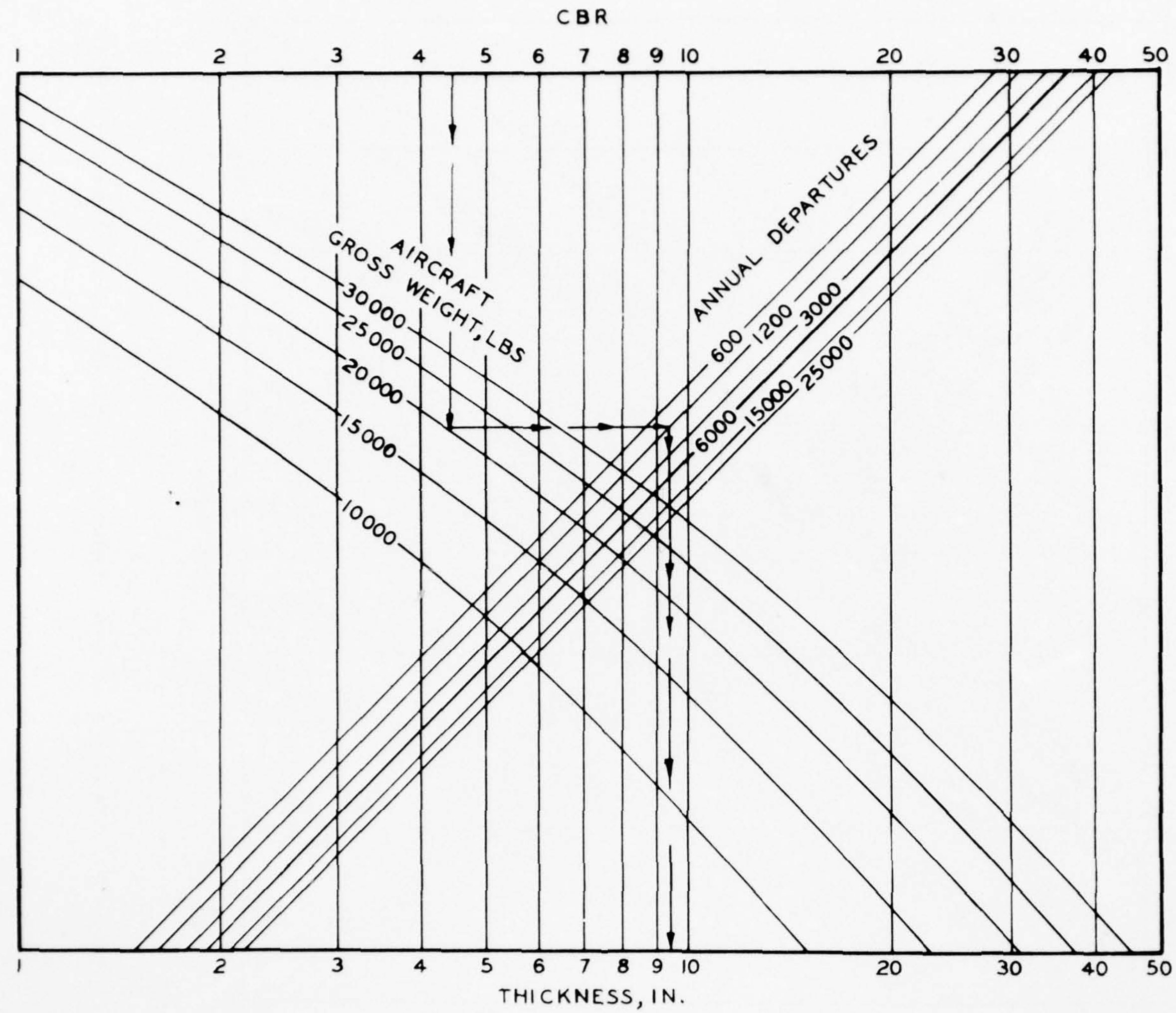


Figure 18. Unsurfaced soil thickness design for dual-wheel gear

7.8 in. This thickness of soil must have a strength equal to the soil strength requirement of 7.2 CBR.

COST-BENEFIT ANALYSIS

The purpose of this section is to familiarize a designer with an approach for comparing rigid versus flexible pavement designs. Differences in material characteristics used in airport construction yield a variance in performance and cost. Rigid and flexible pavements consisting of different quality materials may be designed to achieve the same structural capacity. Each structurally equal section may be comprised of different thicknesses and hence the cost will be dependent on the quality of materials employed. For example, using all-bituminous concrete sections or stabilized bases may reduce the thickness in comparison to conventional flexible pavements or concrete pavements on unbound bases. However, the cost-benefit relationship of each section should be examined prior to deciding upon a given design. A cost-benefit analysis is concerned with selecting the particular physical design based on the total cost of the section anticipated within the expected life of the pavement. This analysis should consider initial costs, maintenance cost, renewal policies, and availability of resources for each local condition.

A simple and direct method of comparing the cost-benefit relationships of rigid and flexible pavements consists of the following steps.

a. First, each particular section is designed for the same design inputs of loading, departures, foundation strength, and material strengths. Using the appropriate design curves, determine the thickness and quality requirements of concrete and base and thicknesses of individual layers in the flexible pavement section.

b. Conduct a total initial cost or price study for each pavement layer. An initial cost is the cost to the contractor of constructing a particular pavement type whereas price is the money an owner may pay to have the project constructed which includes the contractor's cost plus his profit. Initial cost analysis may be obtained by determining cost quotations from suppliers on material costs, construction costs, haul distances, etc. The price will depend on variables of economy, the contractor's production rate, etc., and may be developed from experience within a given geographical area.

or under similar situations. This is the cost required to maintain the facility in a serviceable condition as calculated or estimated for the entire life of the pavement. This value may be expressed as a percentage of the initial construction cost.

d. Calculate and apply, where appropriate, any additional costs or savings that may result from certain construction techniques or ecological requirements, e.g. recycling of materials.

e. Compare and decide on the pavement section to be built after considering both the structural and total cost (initial plus maintenance) aspects of each structurally equal pavement section considered.

APPENDIX A: CONSTRUCTION GUIDANCE FOR THIN CONCRETE PAVEMENTS

Pavement construction procedures have, in general, been developed for rigid pavements ranging in thickness from 8 to 24 in. Slip-form pavers and pavers which operate from fixed side forms have successfully been used to construct pavements for the entire range of thicknesses. However, specialized procedures and precautions are necessary for thicker pavements. This is also true for pavements for light aircraft which will generally be less than 8 in. thick. Thicknesses of pavements for light aircraft will be similar to thicknesses of pavements for secondary roads, building floors, and parking areas, but the smoothness, durability, strength, and quality control requirements will be commensurate with those for aircraft operation.

In this appendix, construction procedures for thin pavements (less than 8 in. thick) will be discussed. Much of the information contained herein will be taken from experience gained in constructing secondary roads,[19-22] thin pavements at the AASHO Road Test,[23-25] thin bonded overlays,[23,24] and floors, parking areas, and driveways.[27-31] Emphasis will be placed on techniques and procedures which will be different from those normally used for construction of airport pavements.[32-34]

MATERIALS

Quality materials are as important for pavements for light aircraft as they are for any other pavement. Quality aggregates, cement, admixtures, water, steel, joint forming materials, joint sealing materials, and materials for protecting and curing are required for a durable, long-lasting pavement. For this reason the material requirements for light-load aircraft pavements should be the same as those for other airport pavements.

The only difference in material specifications should be the maximum size of the coarse aggregate. The maximum size coarse aggregate should not exceed one fourth of the pavement thickness, or one half the clear spacing between reinforcing bars or wires. This will permit satisfactory placement of the concrete and formation of the pavement.

However, from a practical standpoint, it may be advantageous to specify a maximum size coarse aggregate of 1 in. As outlined in Reference 35, the factors of handling, availability, and economy make a 1-in. maximum size aggregate attractive. With a 1-in. maximum size aggregate, the material may be provided in only one separate size. This size material will be available in most locations since many highway departments require at least one size with 1-in. aggregate. Finally, the waste and handling equipment will be reduced if only one aggregate stockpile is used. Considering the amount of concrete involved, the procedures and specifications should be kept as simple as possible.

If a 1-in. maximum size aggregate specification is adopted, the coarse aggregate may be provided in one size and the gradation should meet the requirements of ASTM C-33[36] for size No. 57 material or smaller. Should aggregate with a maximum size greater than 1 in. be permitted, it should be provided in two separate sizes as specified in Item P-501.[32]

MIX DESIGN CONSIDERATIONS

The requirements for the concrete and the specification methods, as set forth in Item P-501,[32] are generally applicable to the construction of light-load aircraft. Minor changes are suggested for the workability requirements for the concrete. These changes are suggested to ensure that thinner pavements (less than 8 in. thick) can be constructed.

When slip-form pavers are used, it is recommended that the maximum permissible slump be increased from 1-1/2 to 2 in. This will permit placement of thinner sections without increasing slumping of the edges as might occur for thicker pavements. A permissible slump of 2 in. is also more in line with highway practices.[37]

When manual (hand) methods are used to strike off, consolidate, and finish the pavement, the maximum slump should be increased to 2-1/2 in., even though internal or surface vibration may be used. The internal vibration would normally be provided by hand-held spud vibrators and surface vibration by a vibrating screed. A 2-1/2-in.

maximum slump is more in line with practices for industrial driveways and parking areas, floors, and slabs.[27-30]

When fixed side forms are used, the size of the job and the pavement thickness will, in many cases, be such that roller screeds (Clary screeds) or pavers using counter-rotating drums and augers (commonly used for placing bridge decks) will be used. Some of these devices employ some form of vibration; others do not. These machines will require concrete with a slump in the 2-in. range for proper placement. The specifications as contained in Item P-501 are probably adequate for use with fixed side forms, but the slump used should be near the high end of the permissible range.

EQUIPMENT

The equipment used for constructing thin pavements for light-load aircraft will probably be smaller, lighter, and less sophisticated than that used for pavements for heavy aircraft and large highway paving projects. However, the equipment must be able to produce uniform consistency concrete, transport and spread the concrete, consolidate the concrete, form the pavement cross section, and finish the surface of the pavement to tolerances required for safe aircraft operation.

Equipment for batching and mixing concrete should meet the requirements contained in Item P-501.[32] Quality concrete with uniform consistency is as important for pavements for light-load aircraft as it is for pavements for heavier aircraft. In some situations, it may be advantageous for the paving contractor to purchase concrete from ready-mix producers. This may be the case when the quantity of concrete is not sufficient to justify the contractor setting up his own facilities or where contractors who might be classified as small business concerns do not have facilities for producing the concrete, but do have the capabilities to construct the pavement. In these situations consideration should be given to the use of ASTM Standard Specification for Ready-Mixed Concrete, Designation: C 94-74.[38] This will eliminate the need for specifications of the batching and mixing equipment and procedures.

The specification has provisions for inserting purchaser requirements; slump (tolerance and specified value), entrained air content (tolerance and specified value), and flexural strength should be inserted.

Pavements for light-load aircraft can be placed with a variety of types of equipment. Forms may be used or a slip-form paver may be used. Small, lightweight slip-form pavers have been developed especially for paving thinner pavements, although the larger, heavy-duty slip-form pavers can be adapted for placing thinner pavements. Figure A1 shows a small machine placing a 4-in.-thick pavement, and Figure A2 shows a large machine placing a 6-in.-thick slab.

On smaller jobs, the contractor may wish to use one of the types of equipment illustrated in Figures A3-A5. Figure A3 illustrates a finisher employing two roller screeds. These are referred to as Clary screeds and may or may not provide vibration. Figure A4 illustrates a type finisher which employs a rotating drum and auger which moves transversely across the pavement. Units using this principle are available for use with and without forms. Units are available with and without vibrators which move across the paving lane with the rotating auger and drum, and units are available with one or two drum-auger combinations. Figure A5 illustrates a vibrating screed which is often used for consolidation and surface finishing on small jobs. Although the pieces of equipment shown in Figures A3-A5 are not equipped with two oscillating-type transverse screeds, as required in Item P-501,[32] they work satisfactorily and should be permitted, especially on smaller jobs where more elaborate equipment would increase pavement cost.

PREPARATION OF UNDERLYING MATERIAL

Only general guidance can be given for underlying material preparation. The desired attributes of the underlying material for pavements for light-load aircraft, such as smoothness, stability, cleanness, and accuracy, are the same as they are for any other type pavement. Because of the thinness of pavements for light-load aircraft, the accuracy of the preparation of the underlying material may be more critical than it is for thicker pavements; i.e., a thickness deficiency of 1/4 in. is

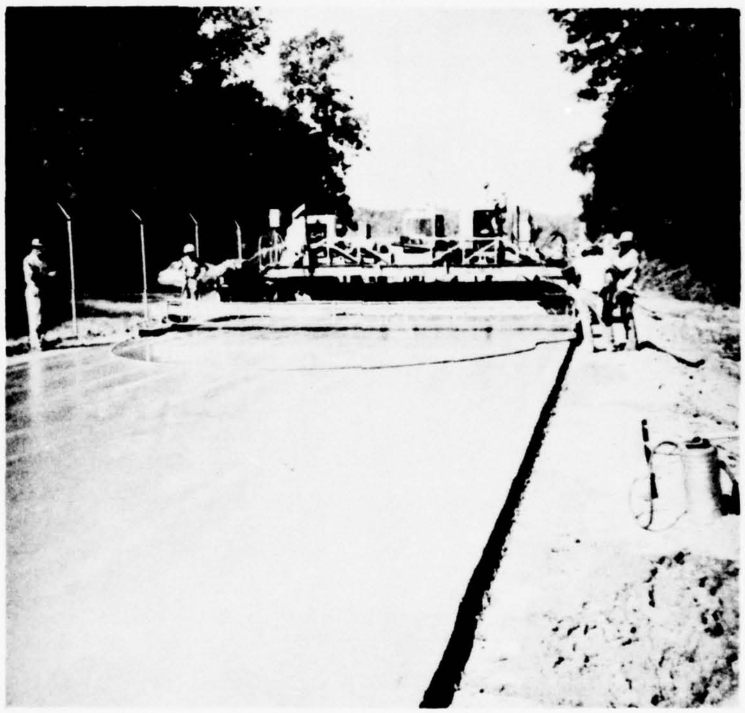


Figure A1. Slip-form paver placing 4-in.-thick pavement

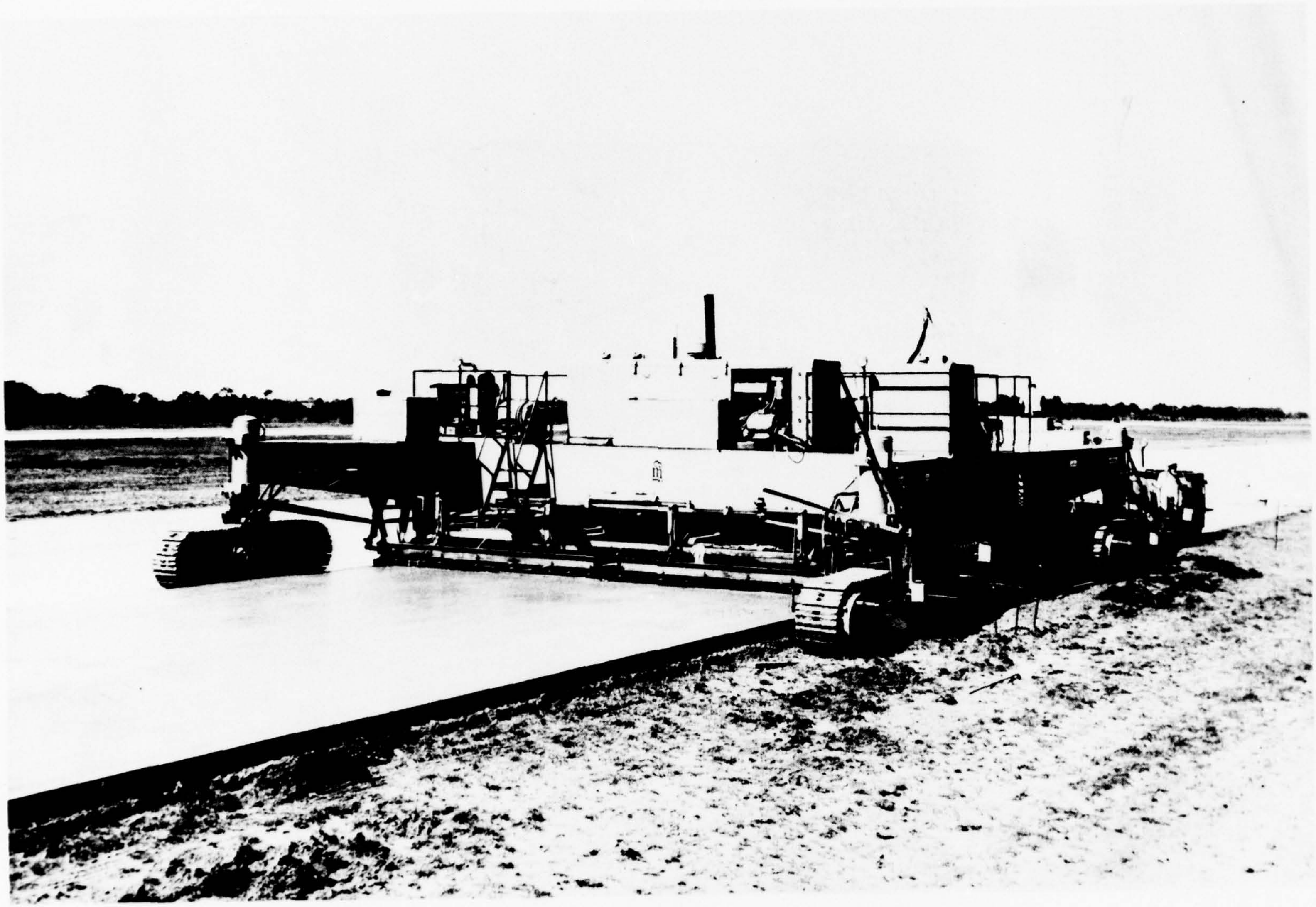


Figure A2. Heavy-duty slip-form paver placing 6-in.-thick pavement

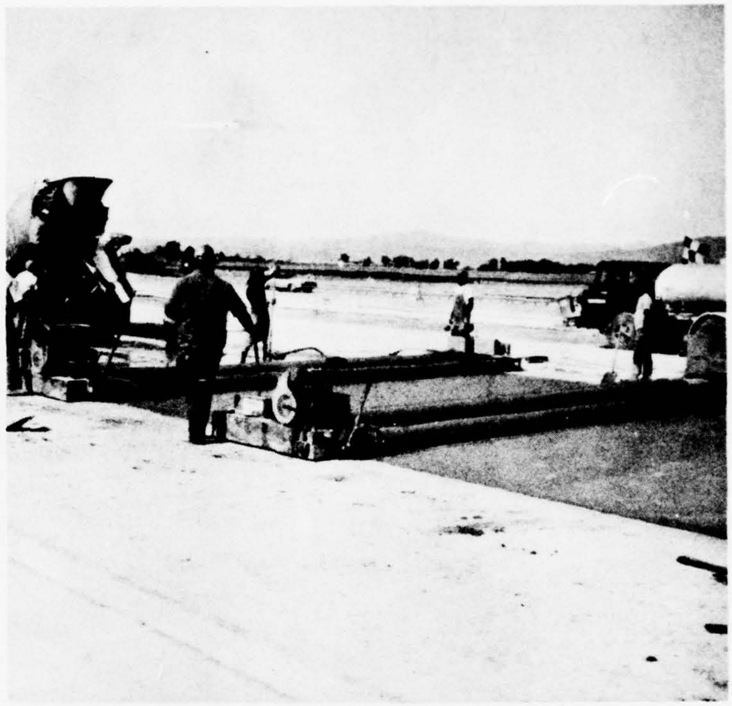


Figure A3. Roller screed finishing machine

Figure A4. Rotating auger-drum combination finishing machine

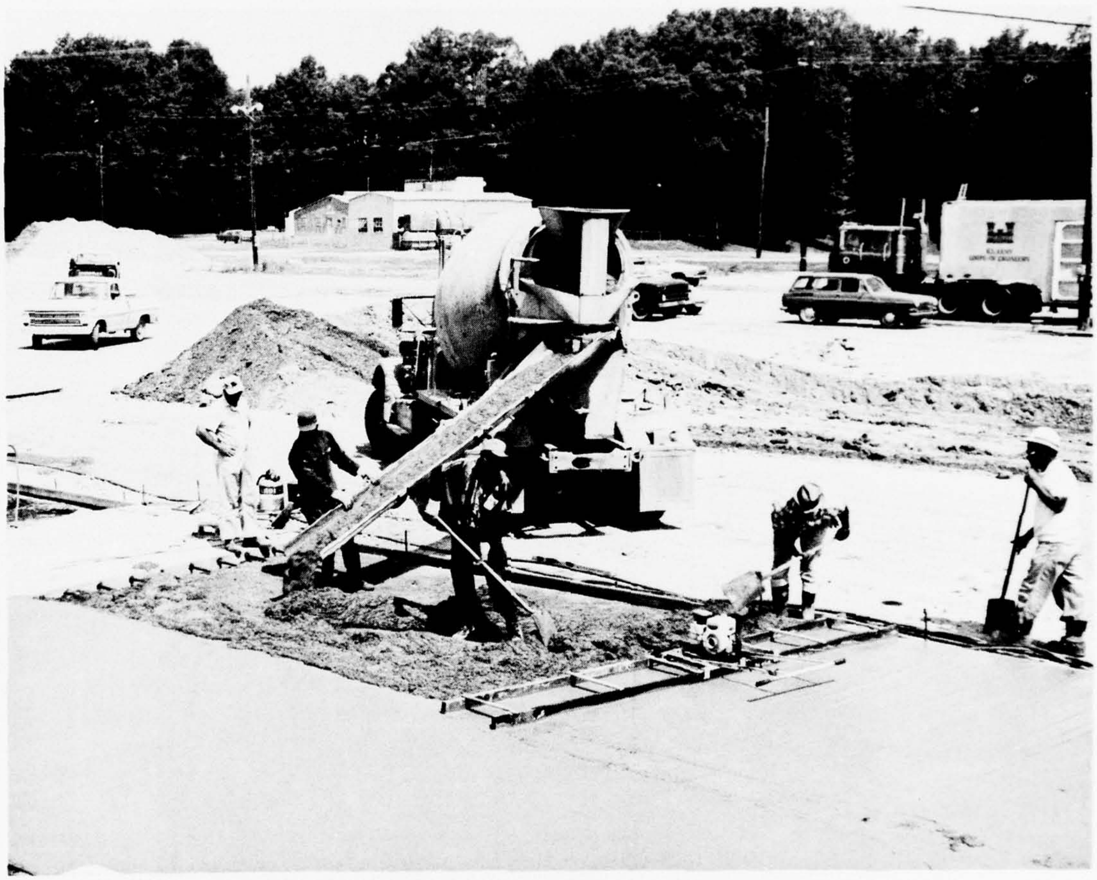


Figure A5. Double beam type vibratory screed

more critical for a 6-in. pavement than it is for a 12-in. pavement. Likewise, the effect of the loss of a certain amount of water, due to improper moistening of the underlying material, will be more critical for a 6-in. pavement than for a 12-in. pavement. If the same amount of water is lost for both the 6- and 12-in. pavements, this will represent a larger percentage of water loss for the 6-in. than for the 12-in. pavement. The problem is compounded because the contractor, especially on smaller jobs, may not have the more sophisticated equipment with features such as automatic electronic grade control. For these reasons it is extremely important that extra care be taken in preparing and maintaining the surface of the underlying material and ensuring that the underlying material has sufficient moisture to prevent it from absorbing moisture from the plastic concrete.

The effects of other parameters are similar, and will be considered in subsequent sections with a detailed treatment of the overall influence on pavement performance being given in the section "Quality Control."

BATCHING AND MIXING CONCRETE

Requirements for batching and mixing concrete for light-load pavements are similar to requirements for other types of pavements, as contained in Item P-501.[32] When ready-mixed concrete is used, batching and mixing should conform to the requirements of ASTM C 94-74a.[38]

Because the exposed surface area to concrete volume ratio increases with decreases in thickness, control of the temperature of the concrete as placed becomes increasingly important for thinner pavements. It therefore is necessary to provide for heating of mixing water and/or aggregates during cold weather concreting, and cooling of the aggregate and/or mixing water during hot weather concreting. The temperature of the concrete, as deposited at the paving site, should not be less than 50° F and not more than 85° F during cold weather construction. During hot weather placement, the temperature of the concrete should be as low as practicable, and never greater

than 90° F. Guidance for heating or cooling of aggregate and water, batching sequences, and mixing procedures should be obtained from ACI recommended practices for hot and cold weather concreting, Designations: ACI 305-72[39] and ACI 306-66.[40]

CONCRETE AND REINFORCEMENT PLACEMENT

The requirements for placing concrete, strike-off of concrete, placement of reinforcement, and consolidation of concrete are contained in Item P-501,[32] and in Order 5370.4, which provides guidance for construction with slip-form pavers. The basic procedures outlined in these documents are applicable to construction of pavements for light-load aircraft. There are, however, several areas where certain precautions should be taken or specialized techniques should be used when constructing thin pavements.

The equipment used to spread the concrete will depend to a great extent on whether or not the haul equipment is permitted to operate on the prepared underlying material. For pavements for light-load aircraft, it may be economically advantageous to place the PCC surfacing directly on the prepared subgrade. In these situations, or when granular subbases with low stability are used, the haul equipment should not be permitted to operate on the prepared underlying material when such operation results in permanent deformations in the underlying material. Therefore, a method will be required to spread the concrete across the full width of the paving lane. Several acceptable types of spreaders are available for spreading concrete. Vibrators should never be used nor should manual spreading be permitted except adjacent to headers, in odd-shaped slabs, or to correct localized deficiencies resulting when spreading is accomplished with a machine. Manual spreading, where permitted, should be done with shovels with square ends. Rakes should not be permitted.

When light equipment or manual techniques are used for placement, extra care should be taken to ensure that the concrete is struck off to the required elevation. Most slip-form pavers have sufficient weight to prevent the strike-off mechanism from floating or riding over high

spots, but equipment such as the rotating screeds (Figure A3) or the vibrating screed (Figure A5) may have a tendency to strike off the concrete to a higher-than-desired elevation. When such equipment is used steps should be taken to ensure that the forming mechanism remains in contact with the forms.

Internal vibration and, on some machines, surface vibration is provided by all slip-form pavers. Vibration of some type should also be provided when forms are used. Because of the thickness of the pavement, the position of internal vibrators is important. The vibrators should not be permitted to touch the underlying material, forms, or dowel bar assemblies. In order to ensure that the entire vibrator is submerged, the vibrators will have to be located with the axis of the vibrator at a small angle from a horizontal plane. According to a study conducted in Colorado,[41] the angle can vary from 0° (horizontal) to 30° without affecting the consolidation. Vibrators having an "L" shape have been developed for consolidating thin slabs and slabs containing reinforcing steel located near the surface. Spud vibrators have also been positioned horizontally with their axis perpendicular to the direction of movement without decreasing the effectiveness of the compaction effort. Should the available equipment, slab thickness, or presence of reinforcing steel prohibit the use of internal vibrators, surface vibration has proven to be adequate for pavements less than 8 in. thick.

Should voids develop along longitudinal construction joints, internal vibrators should be positioned to provide additional compaction effort along the edge. Internal vibration should always be provided adjacent to transverse headers no matter what type of equipment is used. This is particularly important when dowels are located in the joint.

When reinforcing steel is included, the most practical method for placing steel will be to preset the steel on chairs. For pavements 8 in. thick or less the major objectionable features of steel placement on chairs is eliminated, i.e., consolidation of the concrete below the steel. The steel will have less tendency to slide horizontally when

the concrete is placed, the steel can be located accurately, and the amount of equipment is minimized when it is preset on chairs. This method was used for the construction of the 2-1/2- and 3-1/2-in.-thick reinforced concrete pavements at the AASHO road tests.[21,22] Recently, chairs were used to place 3- and 4-in.-thick jointed reinforced and continuously reinforced overlays in Iowa[42] and in Georgia to place 6-, 4-1/2-, and 3-in.-thick continuously reinforced overlays.[43] The bottom lift of concrete below the steel should have a minimum thickness of 2 in.

Other methods of steel placement, such as the double strike-off method or mesh depressors, may be used. However, these methods will require special equipment, and for the double strike-off method, two spreaders. These procedures should not be prohibited, but the simplest and most economical method that provides satisfactory placement should be used.

JOINT CONSTRUCTION

There are no areas of joint construction where specifications should be significantly different for construction of light-load pavements. There are, however, certain areas where the small pavement thicknesses will create the need for extra care and special techniques.

Because the slab thickness will normally be less than 9 in., keyed longitudinal construction joints will not be used. Longitudinal construction joints will normally have vertical faces. The edges may be thickened, dowels may be used, and around the periphery of paved areas, deformed tie bars may be used. Forming the vertical face will present no unusual problems. When slip-form pavers are used, edge slump will not be as much of a problem as it is for thicker pavements. Alignment of dowels is equally as important for light-load pavements as it is for thicker pavements. Because of the limited available cover, proper vertical positioning of dowels and tie bars becomes increasingly important as slab thickness decreases. Installation of dowels and tie bars by insertion into plastic concrete should be checked carefully to ensure that the surface of the slab is not disturbed, i.e., a bump on the surface.

Expansion and transverse construction joints present no unusual problems. Good construction practices and extra care are necessary around these types of joints to ensure adequate consolidation and to prevent excessive surface roughness. Extra vibration with hand vibrators should always be provided adjacent to the header or the joint filler.

There are several aspects of construction of contraction joints for thin pavements which will require close attention. If the weakened plane is to be sawed, the timing of the sawing will be critical, especially for transverse joints. The cause of cracking of the slab will be the tensile stresses induced in the concrete by the shear stresses at the interface between the slab and the underlying material. The resisting forces will be the product of the tensile stresses in the concrete slab and the slab cross-sectional area. Upon initial contraction the shear stresses at the interface will not be caused entirely by sliding friction, but by a combination of sliding friction, adhesion, and mechanical interlock. The stresses due to the adhesion and mechanical interlock will be essentially constant and the tensile stress in the slab will not be completely independent of slab thickness as it would be if the stresses at the interface were caused by frictional resistance to sliding. Therefore, the time of sawing to prevent uncontrolled cracking will be a function of slab thickness. As thickness decreases, earlier sawing will be required. The time of sawing of longitudinal contraction joints is not as critical as it is for transverse joints, but it will be necessary to saw them sooner than for thicker pavements.

Accuracy of the placement of dowels and tie bars in contraction joints is equally as critical as it is for longitudinal construction joints. When tie bar inserters are used, proper orientation and insertion depth will be especially important. When dowels are used in transverse contraction joints, clearance for internal vibrators may be a problem. Because of the limited cover the depth of insertion or the orientation of the vibrators may have to be changed from the normal mode of operation in order to clear the dowel basket assemblies.

FINISHING, CURING, AND PROTECTION

As with many other aspects of construction previously discussed, the thickness of the pavement, while not creating a need for different techniques or specifications, produces conditions that need more care and control to ensure proper construction. Finishing of the surface poses no problems, but there are several aspects of curing and protection of the pavement which pose special problems. These problems stem from the fact that the ratio of the volume of concrete to exposed surface area decreases as the thickness decreases.

Moisture loss will be directly proportional to the exposed surface area. A 6-in.-thick pavement will have the same exposed surface area as an 18-in. pavement if constructed with forms and only slightly less if a slip-form paver is used. Therefore, the moisture loss should be approximately the same for either pavement thickness. In terms of cracking (surface shrinkage cracking and structural cracking), a given moisture loss will be much more critical for the 6-in. pavement than it is for the 18-in. pavement. This points to the need for extra care in preventing moisture loss during curing of thinner pavements. The use of fog sprayers, wet curing methods, or larger application rates for membrane curing compounds may be required, especially under hot, windy, low-humidity conditions.

The ratio of exposed surface area to concrete volume also influences the gain or loss of heat in the concrete. Thin pavements will, therefore, require more effective means for controlling temperature than will thick pavements, especially when curing is occurring under extreme temperature conditions.

During cold weather the rate of heat loss will be proportional to the exposed surface. For a given rate of heat loss, the temperature of a thin slab would be less than that of a thick slab. Compounding the problem is the fact that there will be less heat generated during hydration for thin slabs than for thick slabs since the amount of heat generated is directly proportional to the volume of concrete. The American Concrete Institute Recommended Practice for Cold Weather

Concreting[48] lists combinations of slab thickness, ground temperature, and cement content where insulating will not maintain a 50° F temperature. Under these conditions, heat is lost through both the top and bottom of the slab and the volume of concrete is insufficient to generate enough heat to keep the temperature above 50° F. If such conditions exist, the concrete should not be placed if the average temperature is below 50° F, even if insulation as specified in Item P-501[32] is used. When temperatures below 35° F are encountered during placement of thin slabs, more insulation than is normally required for thicker slabs will be needed. No specific guidance can be given as to the thickness of insulation needed to prevent freezing. Manufacturers' recommendations should be followed and provisions made for removal and replacement should freezing occur.

During hot weather the large exposed surface area to volume of the concrete ratio does not present as much of a problem as it does during cold weather. When there is a loss of heat from the slab, a large ratio is desirable. On the other hand, if there is a heat gain through the exposed surface, a large ratio is undesirable. From the standpoint of temperature of the concrete neither situation appears that critical. The primary problem is one of moisture loss which is accentuated by high temperatures. Because of this a large ratio is undesirable and the use of a water fog to keep the surface damp until the curing medium is applied is critical for thin pavements.

QUALITY CONTROL

Construction control to ensure that a pavement has the desired properties involves establishing limits within which certain parameters must fall, making periodic measurements of the parameters as construction progresses, analyzing the measurements, and prescribing corrective action when established requirements are not met. The specifications, as set forth in Item P-501,32 are applicable to pavements for any type aircraft. The specifications for such parameters as flexural strength and entrained air content will ensure a long-lasting, durable pavement,

and the specifications for surface tests will ensure (at least before permanent deformations occur) that a smooth riding surface is provided.

The tolerances and acceptable ranges for the controlling parameters, as set forth in Item P-501, are adequate for light-load pavements with the exception of the pavement thickness. Control of pavement thickness should be tighter for thin pavements. Closer control is needed with thin pavements because the sensitivity of the tensile stress in the slab to changes in thickness increases with decreasing thickness. This concept is illustrated in Figure A6. In this figure are plotted changes in tensile stresses in PCC slabs resulting from deficiencies in the slab thickness. As an example, the difference between the tensile stress in a 10-in. slab and a 9.85-in. slab is 19 psi, a 10-in. and a 9.75-in. is 32 psi, and a 10-in. and a 9.5-in. is 65 psi. The figure illustrates that the magnitude of the stress difference increases as the thickness decreases. The stress plotted is the edge stress as computed with a slab on a dense liquid foundation model.

The implications of this figure are that smaller tolerances for pavement thickness deficiencies are needed for thinner pavements. For light-load pavements, which will probably be less than 9 in. thick, the magnitude of the stress increase, caused by thickness deficiencies, is rather dramatic. Figure A7 illustrates the effect of thickness deficiencies on the life of a pavement. The pavements were designed for a 30,000-lb dual-wheel aircraft for 3000 annual departures and a life of 20 years. For the various deficiencies in thickness, the decrease in the life of the pavement was calculated and plotted on the abscissa. These plots illustrate that the reduction in pavement life is a function of the design thickness as well as the thickness deficiency. Realistic ranges of soil modulus and flexural strengths were used so that the design thicknesses represent realistic conditions. The plot illustrates that deficiencies in thickness, which are less than the maximum deficiency for full payment (0.2 in.), will cause significant decreases in pavement life. For thicker pavements the decrease in life for deficiencies in thickness up to 0.2 in. would not be so large and the specified limits would be adequate.

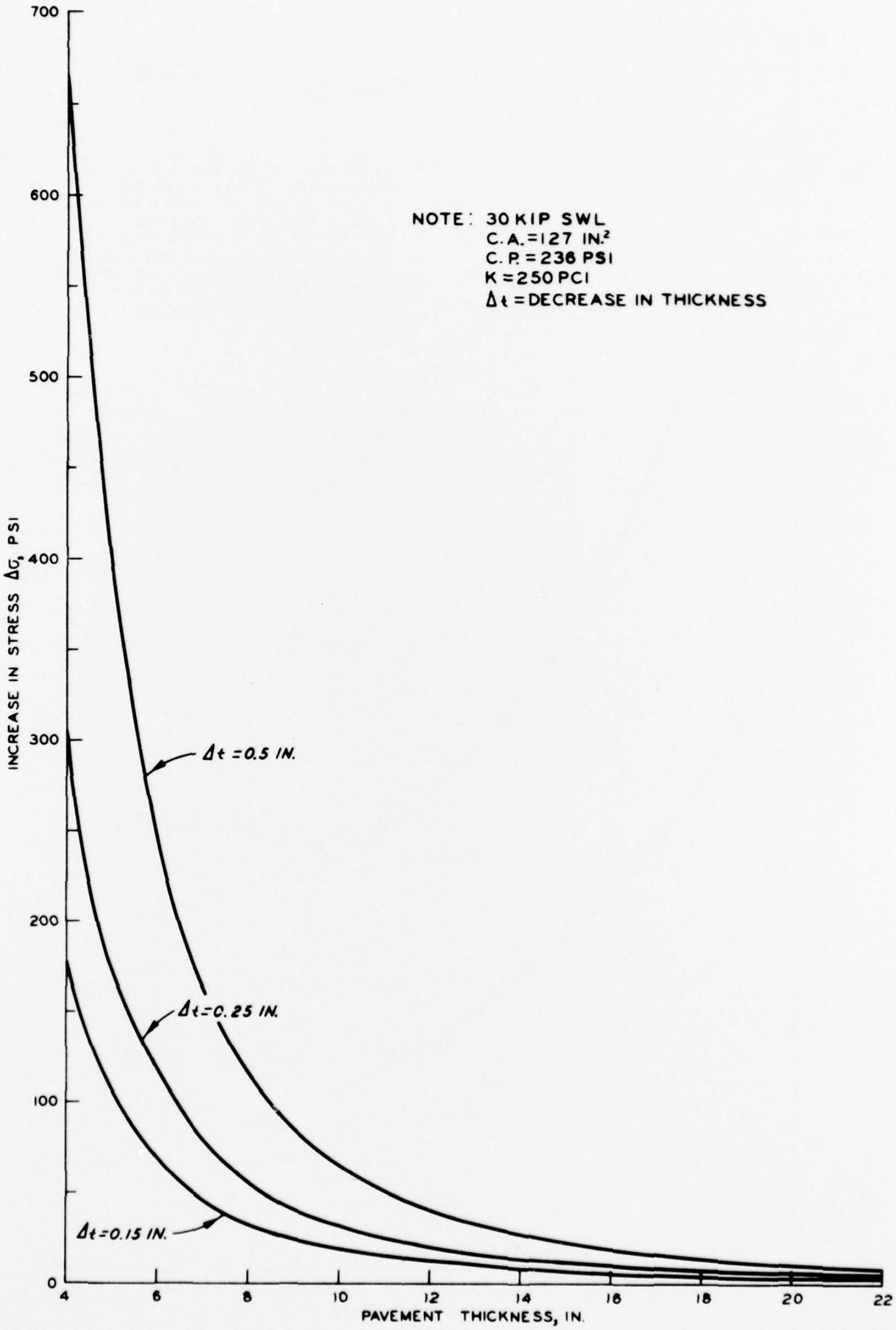


Figure A6. Effect of pavement thickness deficiencies on tensile stress in pavement

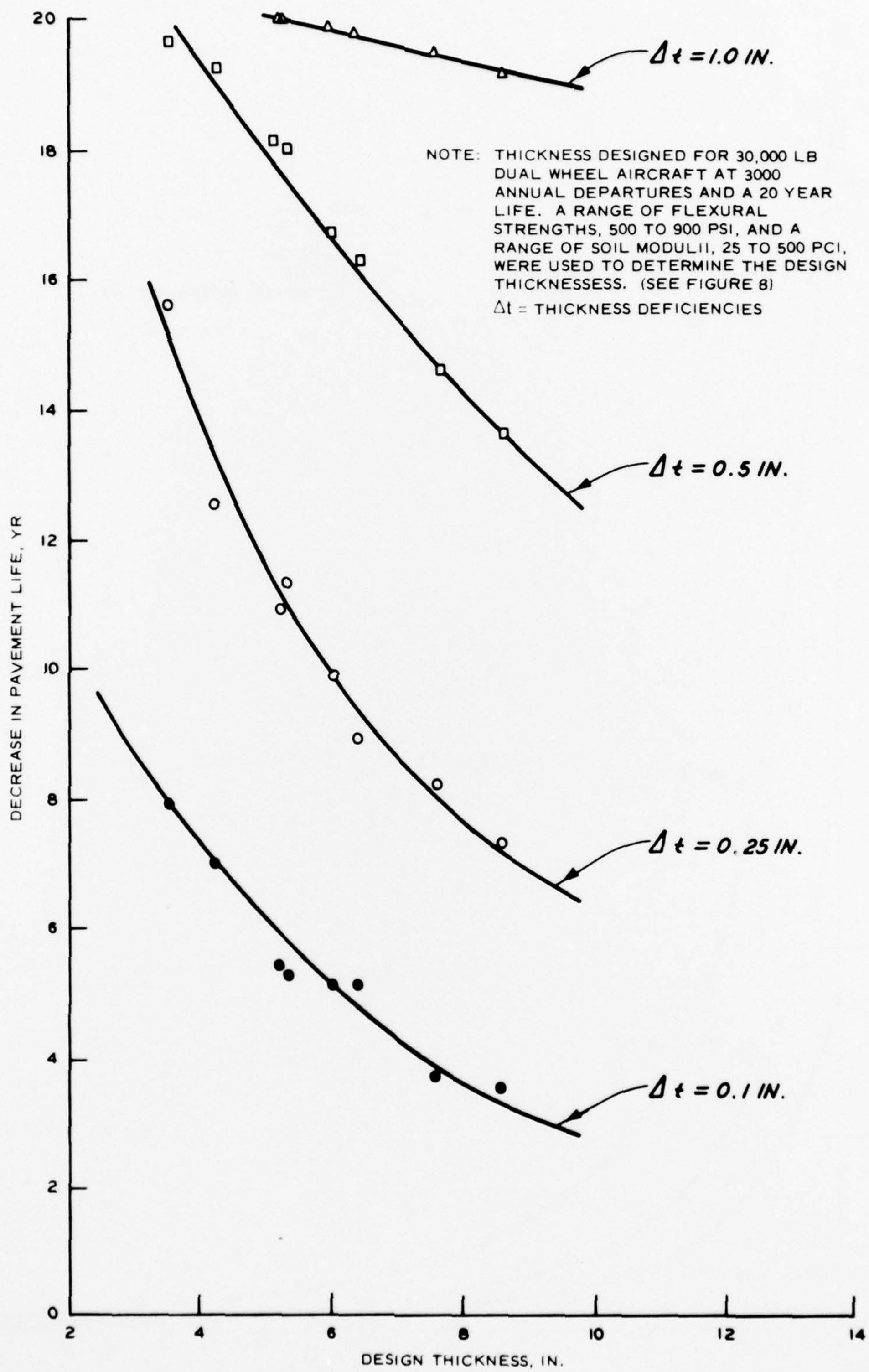


Figure A7. Effect of pavement thickness deficiencies on pavement life

The obvious solution for thin (8-in. or less) pavements would appear to be smaller tolerable thickness deficiencies. However, those presently specified (0.2-in. maximum without adjustment in payment) are based on construction capabilities, i.e., tolerances which can be obtained with available equipment and procedures. To tighten tolerances would be to set unrealistic goals or to increase construction costs. An additional factor which must be considered is the type contractor who will construct light-load pavements. This may very well be a smaller contractor who does not have sophisticated electronically controlled grade preparation and paving equipment.

The most practical solution to the problem appears to be to use current specifications, but to increase the thickness of the slab to prevent excessive reductions in the pavement life because of deficiencies in thickness. This will result in conservative thickness requirements for certain situations but for other situations will eliminate the need for tighter thickness control. The thickness obtained from design charts should be increased by 0.3 in. When the resulting thickness is in fractional inches, the thickness should be increased to the next full inch from fractions of an inch of 0.3 or more and reduced to the lower full inch from fractions less than 0.3 in. This procedure is consistent with the rounding procedure currently used and is designed to prevent problems from developing for those fractional thicknesses of 0.0 to 0.3 in. Considering that full payment is made on deficiencies of from 0 to 0.2 in., the situations where problems may occur are for fractional thicknesses of from 0.9 to 0.99. However, considering the other approximation inherent in the system, this is not considered a serious problem.

An example of how this procedure will affect specified thickness values is illustrated in Table 3. The thickness values from the design chart (Figure 7) were used to prepare Figure A7.

Table 3

Thickness Requirements for 30,000-lb Dual-Wheel Aircraft

Modulus of Soil Reaction pci	Thickness from Design Curve in.	Specified Thickness w/o 0.3 in. Added in.	Specified Thickness with 0.3 in. Added in.
	Flexural Strength = 500 psi		
25	8.6	9	9
50	8.0*	8	9
100	7.6	8	8
200	7.0*	7	8
300	6.4	7	7
400	5.7	6	6
500	5.2*	5	6
	Flexural Strength = 900 psi		
25	6.0*	6	7
50	5.7	6	6
100	5.3	6	6
200	4.8	5	5
300	4.2*	4	5
400	3.8	4	4
500	3.5	4	4

* Thickness values where adding 0.3 in. increased the specified thickness.

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